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16. Abstracts

The results are presented of an investigation which was aimed at providing information for establishing standards on emissions from aircraft activities. This study of emission control technology was initiated in response to requirements of the Clean Air Amendments of 1970. The program consisted of independent investigation of the following topics: Emission control by engine modification; Emission control by ground operations modification; Emission control by fuel modification; and Emission measurement. The investigation of fuel modifications was discontinued after the preliminary analysis. Engine modification control methods were identified through reviews of earlier work and through discussions with engine manufacturers. A list of specific control methods was formulated on the basis of preliminary analyses in which feasibility was indicated. The preliminary list of control methods was then subjected to more detailed analysis of control effectiveness and implementation costs. Ground operations modification control methods were evaluated in a similar manner.

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ASSESSMENT OF AIRCRAFT EMISSION CONTROL TECHNOLOGY

by
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INTRODUCTION

Background

An awareness of air pollutant emissions from aircraft developed in the late 1950's with the introduction into service of turbine-engine aircraft. Visible exhaust plumes from turbojet engines and increased levels of exhaust odors at airports gave rise to complaints against these perceptible manifestations of aircraft emissions. These complaints, in turn, stimulated investigations by public health agencies into the nature and extent of aircraft emissions, and these investigations have continued unabated in the intervening years.

In 1968, Northern Research and Engineering Corporation conducted a survey of information on aircraft emissions and their control. This investigation was sponsored by the National Air Pollution Control Administration and resulted in a comprehensive report on the nature and control of aircraft emissions (Ref 1). This investigation was directed primarily at an assessment of the extent or magnitude of aircraft emissions, and identification of approaches to reducing emission rates. The report represents the state of our understanding of the subject in 1968, and identifies the principal sources of information on aircraft emissions which existed at that time.

Since 1968, several organizations have been active in further investigations of various aspects of aircraft emission control. The NREC staff, in 1969, conducted a detailed analysis of the implementation times and costs of controlling visible smoke emission by "retrofitting" low-smoke combustors in existing turbine engines (Ref 2). In 1970, Scott Research Laboratories completed an investigation of emissions from aircraft piston engines which resulted in the first significant source of information on this subject (Ref 3). In 1971, a series of papers on aircraft emissions were presented at a conference on "Aircraft and the Environment" sponsored by SAE and DOT (Ref 4), and the results of this conference were summarized in a paper by Paullin (Ref 5). These investigations (Refs 2 through 5), in our opinion, have produced the most significant contributions to the over-all subject of aircraft emissions since 1968. There have, of course, been many advances in more specific areas of emission control. Many of these works will be cited later in this report.

The investigation described in this report was initiated in response to requirements of the Clean Air Amendments of 1970. This act calls for the establishment of aircraft emissions standards as specified in Section 231 of the Act. Specifically, this section calls for the investigation of emissions of air pollutants from aircraft to determine:

1. The extent to which such emissions affect air quality in air quality control regions throughout the United States.
2. The technical feasibility of controlling such emissions.

Based upon the information generated under such a study, the Environmental Protection Agency is required to propose emissions standards applicable to any class or classes of aircraft which cause or contribute to air pollution which endangers the public health or welfare, and to establish an implementation schedule commensurate with available technology and reasonable cost of compliance.

In order to carry out the above requirements, the responsibilities within the Environmental Protection Agency were divided. The Bureau of Air Pollution Sciences, Office of Research and Monitoring, had primary responsibility to assess the impact of aircraft emissions on air quality. The Mobile Sources Pollution Control Program, Office of Air Programs, independently initiated a study to assess the technical feasibility of controlling aircraft pollutant emissions and the costs associated therewith.

This report has been prepared for the Mobile Sources Pollution Control Program and is concerned with aircraft emission control technology. A parallel investigation of the impact of aircraft emissions has been conducted by NREC for the Bureau of Criteria and Standards. The results of the impact investigation are contained in a companion report (Ref 6).

Objectives

The over-all objective of the two investigations was to provide information necessary for establishing standards on emissions from aircraft activities. The information required for this purpose falls into the following categories:

1. Methods for controlling emissions from aircraft activities.
2. Instrumentation requirements for measuring aircraft emissions.
3. Rates of emission of various pollutants at airports from aircraft activities.
4. Impact of emissions from aircraft activities in airport vicinities.

Information on emission control methods is necessary to determine the levels to which it is feasible to reduce aircraft emissions. The results of an earlier NREC study (Ref 1) indicated that practical control approaches include modifications of aircraft engines, fuels, and ground operational procedures. Thus, an assessment of control methods must be concerned with each of these categories of approaches. In assessing the feasibility of a control method, three factors must be explored: the cost of utilizing the method, the effects of the method on the functioning or capacity of the aircraft system, and the effectiveness of the method in reducing emissions.

Information on emission measurement instrumentation is necessary to assure that aircraft emissions can be measured with the accuracy and sensitivity necessary to enforce the desired standards. Measurements will be required for engines operated under test conditions in the laboratory and engines being operated while installed in all types of aircraft. It is not necessary, for the purpose of enforcing emission standards, that measurements be taken on engines in moving aircraft, either on the ground or in flight.

Pollutant emission rates at airports are not required specifically in the establishment and enforcement of air quality standards. Presumably, such standards will be based upon instantaneous or cumulative emissions from individual aircraft, or aircraft engines, and associated auxiliary equipment. However, the total emission rate at an airport is an important intermediate quantity required in relating the impact of aircraft emissions to aircraft emission rates and activity levels. Also, the total airport emission rate is used as a gross measure of the importance of an airport as an emission source in the community.

Information on the impact of aircraft emissions is necessary to determine the levels to which it is necessary to reduce emission rates in order to prevent adverse health effects, property damage, or undue annoyance. This information must be in the form of correlations between pollutant levels in the airport neighborhood and the rates of emission at the airport.

The specific objectives of this investigation of emission control technology were:

1. To identify methods of controlling aircraft emissions through modifications of engines, fuels, and ground operations.
2. To estimate the effectiveness of these control methods in reducing aircraft emission rates.
3. To estimate the times and costs of implementing these control methods.
4. To assess the technology of emission measurement as applied to aircraft engines, and to identify areas where advancements in instrumentation or test procedures are required.

Methodology

The program has consisted essentially of independent investigations of the following topics:

1. Emission control by engine modification.
2. Emission control by fuel modification.
3. Emission control by ground operations modification.
4. Emission measurement.

The investigation of fuel modifications was discontinued after preliminary analysis indicated that no significant reductions in emissions can be achieved by modifying fuels, except for reductions in sulfur or lead which result in proportionate reductions of SO_2 and lead emissions.

Engine modification control methods were identified through reviews of earlier work (e.g. Ref 1) and through discussions with engine manufacturers. A list of specific control methods was formulated on the basis of preliminary analyses which indicated that each method was feasibile and offered a significant reduction in one or more emission classes. Feasibility was based on the following factors:

1. No reduction in engine reliability (safety).
2. Little or no reduction in engine performance (power-weight ratio).
3. Reasonable cost of implementation.

The preliminary list of control methods was then subjected to more detailed analysis of control effectiveness and implementation costs. The results of the effectiveness analysis were supplied as input information to the parallel study of impact of aircraft emissions. The predicted effectiveness of each control method in reducing impact at airports is reported in Reference 6.

Ground operations modification control methods were evaluated in a similar manner. Specific methods were identified through discussions with engine manufacturers, airlines, and airport operators. These methods also were subjected to analyses of effectiveness and costs, and their effectiveness in reducing emission impact also has been evaluated in the impact study.

The emission measurement technology assessment consisted essentially of the following steps:

1. Analysis of the accuracy and sensitivity requirements of measurement instruments required for current and future emission levels from aircraft engines.
2. Compilation of information on measurement equipment currently used by engine manufacturers and air quality control agencies, and equipment available from instrument manufacturers.
3. Review of factors affecting the design and selection of measurement equipment, and the specification of test procedures.

In this task, full advantage was taken of the results of other groups which have been active in studying various aspects of measurement of aircraft emissions.

Pollutants Considered

In this program, consideration has been given, in varying degrees, to the following pollutant classes:

- Emission constituents:
  - Carbon dioxide (CO_2)
  - Carbon monoxide (CO)
  - Nitric oxide (NO)
  - Nitrogen dioxide (NO_2)
  - Organic constituents
    - Total hydrocarbons (THC)
    - Reactive hydrocarbons (RHC)
    - Aldehydes (ALD)
  - Dry particulates (DP)
  - Sulfur dioxide (SO_2)
- Sensory effects:
  - Visible smoke
  - Odor

Contributions to these pollutant classes have been considered from the following aircraft sources:

- Engine exhaust
- Crankcase blow-by
- Auxiliary power unit exhaust
- Fuel drainage
- Evaporative emissions

The assessment of measurement technology included all of these emissions except reactive hydrocarbons (RHC). This class is not well defined at the present time.

In the evaluation of emission control methods involving engine modifications, the following emission classes were considered:

- Carbon monoxide (CO)
- Nitrogen oxides (NO_x)
- Total hydrocarbons (including drained fuel)
- Dry particulates (including smoke)

Reactive hydrocarbons and aldehydes were not included since no correlations exist between engine design characteristics and emission rates for these classes, and no control methods have been developed. SO_2 emissions were not considered since these are directly related to the sulfur content of the fuels burned and are independent of engine characteristics.

In the evaluation of emission control methods based on ground operations modifications, reductions in RHC, ALD, and SO_2 emissions were considered in addition to those considered with engine modifications.

Report Contents

The principal results and conclusions of the program are summarized in the following sections of the report. Detailed descriptions of the methodology and results of the analyses of control methods and measurement methods are contained in later sections of the report.

Background information in each of the analysis areas is rather limited. For further information on the nature of aircraft engines and their emissions, an earlier NREC report (Ref 1) is suggested. The companion report on impact of aircraft emissions (Ref 6) also is recommended as a source of related information.

SUMMARY OF RESULTS

Emission Control by Engine Modification

Engine Classification

To facilitate analyses of engine modifications, aircraft engines have been categorized according to their thrust or power level as follows:

Engine Class	Engine Type	Power Range (lbf-thrust or ESHP)
T1	Turbine	Less than 6000
T2	Turbine	6000 to 29,000
T3	Turbine	Greater than 29,000
P1	Piston	(Includes all opposed configuration engines)

This classification system, although it is based simply upon thrust level, effectively separates engines of similar emission potential. Also, the effectiveness and costs of control methods can be considered to be similar for all engines within each class. Thus, the classification system has been particularly useful for this program and may also provide a rational basis for the definition of emission control standards. Specific engine families within each class and their characteristics are discussed in the report section entitled AIRCRAFT ENGINE CLASSIFICATION.

Emission Control Methods

Turbine Engines

Six control methods involving engine modifications have been identified which are applicable to existing turbine engines. The control methods and the pollutant classes which they are intended to control are as follows:

Control Method	Pollutant Classes Controlled
Combustor redesign (minor)	CO, THC, NOx, DP, Smoke
Combustor redesign (major)	DP, Smoke

Control Method	Pollutant Classes Controlled
Fuel drainage control	THC
Divided fuel supply	CO, THC
Water injection	NOx
Compressor air bleed	CO, THC

The first control method consists of simple modifications of the combustor and fuel nozzle to reduce all emission rates to the best levels currently attainable within each engine class. The degree of control attainable depends upon the performance of specific engines with respect to those engine in the same class demonstrating best emission performance. Each of the other control methods is more specifically directed at one or two pollutant classes.

Two control methods have been identified which are considered to be applicable only to future engines as the design concepts involved could not readily be incorporated into engines already designed. These control methods are:

Control Method	Pollutant Classes Controlled
Variable-Geometry Combustor	CO, THC, NOx, DP, Smoke
Staged Injection Combustor	CO, THC, NOx, DP, Smoke

These control methods involve advanced combustor design concepts and, as indicated, would be effective in controlling all pollutant classes considered.

The actual reduction in emission rate achieved through the use of a control method varies with the pollutant considered, the engine class, and the engine operating mode. Estimates of the effectiveness of each control method have been made for all combinations of these factors and are presented in the report section entitled EFFECTIVENESS OF CONTROL METHODS: ENGINE AND FUEL MODIFICATIONS.

Piston Engines

Seven control methods have been identified which are considered to be feasible for application to existing aircraft piston engines.

These methods have been developed primarily for the control of THC and CO emissions from automobile engines. Control methods for NOx emissions have not been included since aircraft piston engines of current design operate at rich fuel-air ratios and, as a result, their NOx emission rates are very low compared to those from automobile engines. The installation of any of the THC and CO control methods would not be expected to increase NOx emissions significantly. The control methods applicable to existing piston engines are as follows:

Control Method	Pollutant Classes Controlled
Simple Air Injection	CO, THC
Thermal Reactor	CO, THC
Catalytic Reactor	CO, THC
Direct-Flame Afterburner	CO, THC
Water Injection	CO, THC
Positive Crankcase Ventilation	THC
Evaporative Emission Control	THC

With regard to future piston engines, various design modifications can be introduced for reducing emission rates. For this study, these modifications have been regarded collectively as one control method as follows:

Control Method	Pollutant Classes Controlled
Engine Redesign	CO, THC

The modifications included in this control method would be similar to modifications which have been introduced in recent years by automobile manufacturers to achieve moderate reductions in exhaust emissions. They do not include the control methods listed above for existing engines, but may include auxiliary devices required for NOx control. Estimates of effectiveness for piston engine control methods are presented in the report section entitled EFFECTIVENESS OF CONTROL METHODS: ENGINE AND FUEL MODIFICATIONS.

Implementation Costs and Times

Existing Engines

The cost and time requirements of applying each control method applicable to existing engines have been estimated. These estimates are of a preliminary nature and are intended to indicate the order of the costs involved in controlling emissions from all civil and military aircraft. Cost and time requirements have been estimated separately for control method development and implementation. Development includes all effort required through certification of the control method for a specific engine family and tooling for production. Implementation includes initial installation of the control method on all engines of a family, and any additional effort or materials costs associated with the control method throughout the remaining service life of the engine.

Since very few of the control methods have actually been developed or applied to aircraft engines, and since many factors affect total implementation costs, many uncertainties are involved in the estimates. The estimates of development costs and times are considered to be reliable. Their accuracy is judged to be within a factor of about 2. That is, the true costs and times of control method development probably lie within a range between 50 and 200 per cent of the estimates. The estimates of implementation costs are considered to be less reliable. The cost and service life of a modified engine component cannot be predicted accurately. Yet these factors strongly affect the cumulative costs of operating and maintaining the modified engine. This uncertainty is unfortunate since the implementation costs could be far greater than the development costs for some control methods. Thus, the estimates of implementation costs can only be regarded as indicative of cost penalties which might be involved with control method implementation.

In the table below, estimates are given of the development time, development costs, and implementation cost for application of each control method to the current population of civil engines.

Turbine Engines

Control Method	Development Time (years)	Development Cost (10^6 dollars)	Implementation Cost (10^6 dollars)
Combustor redesign (minor)	2 1/2 - 5	37	343
Combustor redesign (major)	5 - 7 1/2	74	589
Fuel drainage control	3 - 5 1/2	35	44
Divided fuel supply	5 - 7 1/2	84	102
Water injection	2 1/2 - 4	25	151
Compressor air bleed	4 - 6 1/2	90	58
	Piston Engines		
Simple air injection	1 1/2 - 3	9	165
Thermal reactor	3 - 6	25	424
Catalytic reactor	2 1/2 - 5	22	535
Direct-flame afterburner	3 - 6	25	424
Water injection	1 1/2 - 3	9	81
Positive crankcase ventilation	1 - 2	4	94
Evaporative emission control	1 1/2 - 2 1/2	4	269

The development times listed above are the times required to reach the point where installation of the control methods in existing engines could begin. Installation of any control method in all existing engines would require an additional time period which is dependent primarily on the availability of engine maintenance facilities. The minimum time for implementation is estimated to be 2 1/2 years for turbine engines and 5 years for piston engines.

As indicated, the costs estimates are based upon the current engine population. Since this population will be different by the time any of the control methods could be developed, the implementation costs also will be different. This difference represents an additional source of uncertainty with regard to implementation costs.

To put the implementation costs in a different perspective, they may be expressed as fractions of total engine costs. For a typical Class T2 (turbine) engine, the cost of installing and maintaining control methods ranges from $4500 to $61,000, assuming a 10-year engine life. Based on a total engine cost of $250,000, these control method implementation costs represent 2 to 25 per cent of the total engine cost. For a typical piston engine, control method implementation costs estimates range from $600 to $4000, also based upon a 10-year engine life. For a total engine cost of $6000, these implementation costs represent 10 to 65 per cent of the total engine cost.

The turbine engine cost and time estimates were developed by using the application of low-smoke combustors to the JT8D engine family as a reference case. Requirements for this case, which is considered to be a minor combustor redesign for a class T2 engine, were estimated in detail in 1969 (Ref 2). Requirements for other control methods were determined essentially by proportioning the costs and times according to the complexity of the method with respect to the reference case. Requirements for other engine classes were determined by using appropriate scaling factors and again using the reference case as a basis.

The piston engine time and cost estimates are based largely on experience to date with emission control from automobile engines.

The methodology used in developing these estimates and the various elements of the total cost and time estimates are discussed later in this report. Similar cost estimates are presented for military engines.

Future Engines

Cost estimates also have been developed for incorporation of emission controls in future engines, that is, engines which have not yet been developed. These estimates have been defined only as fractions of total engine cost since no reasonable basis is available for estimating the numbers of engines which would be affected.

Emission control in turbine engines attained through the use of advanced combustor design concepts is estimated to represent an increase in total engine cost of 3 to 4 per cent. Emission control in piston engines achieved by engine design modifications probably would not result in any significant increase in engine cost. However, if greater control of emissions is required than can be achieved by engine design modifications, one or more of the control methods applicable to existing engines will be necessary. The costs of these control methods, which involve the addition of auxiliary devices such as thermal reactors, will be significant-- probably in the range of 5 to 10 per cent of total engine cost.

These cost estimates represent the increased costs of new engines with emission controls installed. It is reasonable to expect additional continuing costs for maintenance of the control methods. These maintenance costs would be similar to those for modification of existing engines which were estimated to represent 2 to 25 per cent of total turbine engine costs and 10 to 65 per cent of total piston engine costs.

Emission Control by Ground Operations Modification

Definition of Ground Operations

The cycle of operations performed by an aircraft during its arrival at and departure from an airport can be defined quite precisely since most of these operations are prescribed by airport or aircraft operating procedures. Characteristic operating or LTO (landing-take-off) cycles have been defined for various classes of aircraft for purposes of estimating pollutant emissions (Refs 1, 3, and 6).

The LTO cycle can be separated logically into flight and ground operations. Flight operations include the approach and climb-out modes as well as the landing and take-off runs, even though the latter occur on the ground. Ground operations include the taxi and idle modes of the cycle and, for purposes of this study, all servicing and support operations which involve emission sources. This separation is logical for two reasons. First, flight operations as defined here are those which cannot readily be modified as an approach to reducing pollutant emissions. Second, flight operations are conducted almost entirely with aircraft engines at full or part power, and under these conditions, pollutant emission rates are quite different from those at the low power levels which are characteristic of ground operations. Aircraft ground operations contribute substantially to concentrations of CO and THC which exist at air carrier airports because of the relatively high emission rates of these pollutant classes at low engine power levels, and because ground operations are largely confined to limited areas within the airport boundaries.

Emission Control Methods

Seven methods have been identified which offer some degree of control of CO and THC emissions at air carrier airports by modification of ground operational procedures. These methods, which under preliminary analysis were judged to be feasible, are as follows:

1. Increase engine speed during idle and taxi operations.
2. Increase engine speed and reduce number of engines operating during idle and taxi.
3. Reduce idle operating time by controlling departure times from gates.
4. Reduce taxi operating time by transporting passengers to aircraft.
5. Reduce taxi operating time by towing aircraft between runway and gate.
6. Reduce operating time of aircraft auxiliary power supply by providing ground-based power supply.
7. Manually remove fuel from fuel drainage reservoirs.

The first two methods reduce emissions by requiring engines to be operated at more efficient power settings, and the next four methods reduce emissions by reducing operating time of either main or auxiliary engines. The effectiveness of these methods in reducing emissions varies considerably, but certain methods (2 and 5), if implemented, would reduce total CO and THC emissions to approximately one-half their current levels at air carrier airports.

The control methods listed above are not, in general, applicable to small, piston-engine aircraft, and, therefore, do not offer means for controlling emissions at general aviation airports. Delay times at take-off are significant at some general aviation airports. However, general aviation operations are not sufficiently controlled for a system of controlled gate departures or engine start-up to be effective in reducing delays. If emissions at general aviation airports are to be controlled, control methods involving engine modifications must be used.

Implementation Costs and Times

The cost and time requirements of the control methods involving ground operations modifications have been estimated for one specific airport (Los Angeles International). These estimates involve many uncertainties and, therefore, must be regarded as preliminary. The estimates are considered to be accurate within a factor of 2. That is the true costs and times of implementation at the airport considered probably are within a range of 50 to 200 per cent of the estimates. The estimates are as follows:

	Control Method	Time (years)	Initial Cost (10^6 dollars)	Annual Operating Cost Change (10^6 dollars)
1.	Increase engine speed	0	0	8.5
2.	Increase speed, reduce number	0.3	0	-3.0
3.	Control gate departure	5	15	-1.6
4.	Transport passengers	2.5	65	5.0
5.	Tow aircraft	1	1.2	417
6.	Reduce APU operation	0.5	1.3	1.5
7.	Manual drainage	0.5	0.04	3.0

Implementation of these methods at other airports would involve costs of the same magnitude. However, the actual costs would vary with activity level and the present availability of auxiliary equipment.

Emission Measurement Technology

Sampling and Test Procedures

Obtaining a representative sample of exhaust gas from an aircraft engine for analysis of emission rates is not a trivial procedure.

The requirement is difficult at the outset with turbine engines because of the jet blast environment in which the sampling equipment must be installed. Beyond that problem, the following factors are all found to have significant effects on the composition of the exhaust sample:

Engine power level
Timewise and spatial variations of exhaust composition
Sampling line diameter, length, material, and temperature
Ambient temperature and humidity
Ambient pollutant levels

Procedures for sampling and analyzing turbine engine exhaust gases have been under development for several years by engine manufacturers and various government agencies. More recently the Society of Automotive Engineers E-31 Committee has been formed to standardize these procedures. Standardization of measurement techniques will minimize the variations due to the factors listed above. However, the sources of error in collecting samples and the variability of samples among different engines must be considered in the establishment of emission control standards.

Sampling requirements for aircraft piston engines can be expected to be similar to those for automobile engines. There are no apparent factors which would cause variability in exhaust samples beyond those factors already recognized with automobiles.

Emission Measurement Instrumentation

Measurement of concentrations of most pollutants in exhaust samples from aircraft engines is generally within the capabilities of existing instruments, and will remain so even with modifications of engines to reduce emission rates. The ranges of accuracy and sensitivity which are required for aircraft emission measurements are discussed later in this report.

The various types of instruments which are available and in current use for aircraft emission measurement have been reviewed. Instruments which appear to be most suitable for measurement of turbine engine emissions at the present time are as follows:

Pollutant Class	Instrument Type
CO and CO_2	Non-dispersive infrared (NDIR)
THC	Heated flame ionization
NO	Chemiluminescence
NO_2	Non-dispersive ultraviolet (NDUV)
Smoke	SAE Smokemeter (ARP 1179)
Particulates	None
SO_2	Determined from fuel analysis
Aldehydes	3-MBTH
Odor	Human odor panel

Even though a suitable instrument for particulate measurement is not available, emission rates of dry particulates can be estimated on the basis of smokemeter measurements. These instruments and alternative equipment are discussed in the APPENDIX.

CONCLUSIONS

From the results of this program, it is possible to formulate conclusions on the costs of various emission control methods and the effectiveness of these methods in reducing emission rates from aircraft engines. The effectiveness of these control methods in reducing impact of aircraft emissions at airports is discussed in Reference 6.

In evaluating control method effectiveness, an order of magnitude system has been used which is based upon multiple factors of two in emission rate reduction. The system is as follows:

Order of Effectiveness	Emission Reduction Attainable (Per Cent)	Fraction of Emission Rate Remaining
1	50	0.50
2	75	0.25
3	90	0.10

This system is useful for comparing emission control methods.

The following conclusions pertain to the control of emissions from turbine-engine aircraft at air carrier airports:

1. First order reductions in CO and THC emission rates can be achieved by modifying aircraft ground operations. If these reductions are achieved by modifying engine operating power levels and reducing the number of engines used in taxi operations, the costs will be negligible, and the controls can be implemented immediately. A reduction in odor levels at airports should accompany the THC emission reduction.
2. First and, possibly, second order reductions in CO and THC emission rates can be achieved by engine modifications. Various alternative methods are available for achieving these reductions, but the cost of implementing any of these methods in the air carrier aircraft fleet will be of the order of 100 million dollars. The time required to implement any engine modification control method in the air carrier fleet will be from 5 to 10 years.

3. A second order reduction in NOx emission rates can be achieved through the use of water injection during take-off and climb-out operations. The cost of applying this control method to the air carrier fleet is estimated to be approximately 100 million dollars, and 5 years or more will be required to implement the method. The degree of control can be reduced or increased by reducing or increasing the rate or duration of water injection. However, the costs will not vary proportionately.
4. A first order reduction in particulate emissions can be achieved by major modifications of combustors, but at very high cost (600 million dollars) and with long implementation times (7 to 10 years). The reduction in particulate emissions that would result from minor combustor modifications would be less than first order.
5. Visible smoke emission from turbine engines can be substantially reduced by minor combustor modifications, and such modifications are being implemented for certain engines. The additional cost of eliminating smoke emission from all air carrier aircraft is estimated to be of the order of 100 million dollars.
6. Second or third order reductions in CO and THC emissions and first order reductions in NOx and particulate emissions will accompany the introduction of advanced combustor design concepts in future engines. Complete elimination of visible smoke and substantial reductions of odor will accompany these advanced designs. Associated costs will be of the order of 3 per cent of the total engine cost. Engines with these features will not appear in service before the late 1970's.

The following conclusions pertain to the control of emissions of piston engines at general aviation airports:

1. First order reductions in CO and exhaust THC emission rates

can be achieved by simple air injection systems. Retrofitting costs would be of the order 200 million dollars with an implementation time of approximately 6 years.

2. Reductions as high as third order in CO and exhaust THC emissions can be achieved by more advanced control methods such as thermal reactors or catalytic reactors. Retrofitting costs would be of the order of 500 million dollars and implementation times would be 8 years or more.
3. Effectiveness of THC emission control from piston engines can be increased by nearly one order of magnitude if positive crankcase ventilation is combined with another THC control method. PCV would not be effective alone because of the fuel-rich operating conditions of aircraft piston engines. The cost of applying PCV to existing piston engines would be of the order of 100 million dollars.
4. First order reductions in CO and THC emissions can be anticipated in future engines by modifications of combustion chambers and control systems. Higher order reduction can be obtained by combining engine design modifications with auxiliary control devices. Emission control in future engines may result in increased engine costs up to 10 per cent, depending upon the degree of emission control achieved. Emission control could be incorporated in new aircraft piston engines by the mid-1970's if initiated now.
5. Lead emissions from aircraft piston engines could be reduced by the use of low-lead or lead-free gasoline. These reductions could result directly from the control of lead, or could be incidental to the use of catalytic reactors for CO and THC control. The cost of low-lead fuels would be approximately 10 per cent greater than current fuel costs.

The technology of emissions measurement will be adequate to support emission control standards requiring first, second, or third order reductions in emission rates when sampling and test procedures have been refined and standardized.

AIRCRAFT ENGINE CLASSIFICATION

The objective of this program is to evaluate the effectiveness, costs, and time requirements associated with the application of emission control methods to aircraft engines. The program is concerned with engines in current use and engines which will be in service during the next ten years. The evaluation of current engines will be based upon the application of control techniques to specific existing engines, whereas the evaluation of future engines will necessarily be based upon projections of future engine characteristics and populations. The purpose of this section is to identify the specific engines which will be included in the analysis of current engines.

Engines to be considered include both turbine and piston engines, and military as well as civil aircraft engines will be included. The general relationship between the engines and the aircraft classification system is illustrated in Table 1.

Turbine engines will be considered by "family". That is, all engines with the same basic model number, e.g., JT9D or CF6, will be considered as a single engine type. This approach is reasonable since, in most cases, a family of engines has a common combustion system design, and, hence, the emission characteristics of all engines of the family will be similar. This approach also is advantageous in that the number of engines to be analyzed is limited to a reasonable level.

Piston engines also will be considered by family wherein the family designation, e.g., IO-200 or TIO-360, indicates the use of fuel injection or turbocharging as well as the engine displacement.

Engine Population

Engines to be considered in this analysis are listed in Tables 2 through 5. Estimates of the numbers of civil aircraft engines in current use are included. Civil aircraft engines are identified separately as air carrier or general aviation types in Tables 2 and 3. Military aircraft engines are identified in Table 4, and current population data are provided. Since this information on military engines is not readily available, the results presented must be assumed to be reasonable approximations. Helicopter and V/STOL aircraft engines are listed separately in Table 5.

Engine Classification

An engine classification system is required to facilitate the analyses of effectiveness and costs of specific emission control methods. This classification should also provide a rational basis for the application of emission standards in the event that standards are deemed necessary. For these purposes, the method of classification should separate engines into categories wherein all engines have similar emission rates when normalized according to an appropriate engine size parameter. Also, the feasibility and effectiveness of control methods should be similar for all engines within a single category.

The classification system which has been adopted is indicated in Table 6. Three classes of turbine engines are defined, and all piston engines are included in a single class. The system is effective in that it separates engines according to their principal applications, and also according to certain design characteristics which affect emission rates.

The small turbine engine class (T1) includes most turboshaft and small turbojet engines used in business aircraft. These engines should be considered separately because the relatively small size of the combustor components (or large surface-volume ratio) makes control of certain emissions more difficult than with larger engines.

The next turbine engine class (T2) includes most turbojet and turbofan engines used in medium to large commercial aircraft. The design characteristics of most of these engines are basically similar.

The third turbine engine class (T3) includes large turbofan engines for "jumbo" transport aircraft and the SST engines currently in use or under development. A grouping of the engine populations according to this classification system is presented in Tables 7 and 8 for aircraft turbine and piston engines respectively.

Within each of these classes, engine emission rates can be expected to be similar when expressed as an emission index (lb/1000 lb-fuel). Emission rates of all pollutants can be correlated effectively with fuel rate and other parameters indicating the engine operating condition such as power level (turbines) or fuel-air ratio (piston engines). The emission index is in widespread use as a correlating parameter, and can be converted readily to other bases such as lb/hp-hr or lb/lb-thrust-hr by using appropriate specific fuel consumption parameters.

It is expected that this engine classification will suffice for purposes of this program and for definition of emission standards for existing engines. The system may require modification, however, as new engines and engine types are developed.

A summary of the number of engines and engine "families" in the total current population and in the categories of air carrier, general aviation, civil aviation, and military aviation is presented in Table 9 by class.

EFFECTIVENESS OF CONTROL METHODS: ENGINE AND FUEL MODIFICATIONS

Introduction

An analysis has been conducted of the technology of emission control for aircraft engines by means of engine or fuel modifications. The purpose of this analysis was to identify specific methods of reducing pollutant emissions from aircraft, and to indicate the reductions in emission rates attainable by these methods. Various engine modifications have been identified which appear to be feasible in the sense that they can be applied to aircraft without degrading engine reliability or seriously reducing aircraft performance. The costs of implementing these control methods also appeared to be within reasonable limits, at least from preliminary analysis. However, implementation costs of these control methods have been evaluated in more detail, and the results of this cost evaluation are presented in the next section of this report.

Control Methods

Turbine Engine Modifications

Control methods considered feasible for turbine engines are listed in Table 10. Six methods are, at least in principle, applicable to existing engines by retrofitting of new or modified parts, and to engines currently in production. Two methods are considered to be applicable only to future engines since the modifications required are too extensive to be applied to engines for which development has been completed. These methods have been identified in previous NREC studies of gas turbine combustor design concepts and through discussions with engine manufacturers. The methods are described in the following paragraphs.

Minor Combustion Chamber Redesign

A minor combustion chamber redesign is defined in this analysis as a modification of the combustor liner or fuel nozzle, or both, not involving a change in design concept. Such modifications generally result in changes in airflow distribution or fuel spray pattern within the combustor. The modification being made currently to JT8D engine combustors for control of smoke emission is considered to be a minor combustion chamber redesign. This control method could be used to reduce all emissions from conventionally designed combustion chambers. However, it is not likely that emission rates could be reduced substantially below the lowest rates which have been achieved in existing engines.

Major Combustion Chamber Redesign

A major combustion chamber redesign is defined as a modification of the combustor liner and fuel nozzle incorporating an advanced fuel injection concept. This modification would involve discarding a conventional liner and pressure-atomizing fuel nozzle combination, and substituting a new combustion chamber with a carbureting or prevaporizing fuel injector. This type of combustion chamber is being used in some engines of recent design (e.g., CF6 and F101), and its use results in substantial reductions in particulate and smoke emissions (Refs 12 and 13).

Other changes in combustor design could be included in this control method, such as the substitution of an annular combustor for a canannular combustor or the introduction of variable geometry. However, changes such as these are not considered feasible for existing engines.

Fuel Drainage Control

This control method is concerned with the dumping of fuel which results from the draining of fuel manifolds at engine shut-down and start-up. At present, this drained fuel is collected in a drainage reservoir in many civil engines, and the reservoir is emptied automatically during take-off or climb-out operations. The drained fuel is discharged to the atmosphere. In some military engines, the fuel is drained directly onto the ground at shut-down and start-up.

A fuel drainage control system is defined here consisting of an automatic transfer system for emptying the fuel drainage reservoir and returning the fuel to one of the aircraft fuel tanks. In the definition of this system it is assumed that drainage of fuel manifolds at engine shut-down and start-up will continue to be required. The drainage control system would be an additional mechanism permanently installed in each engine to eliminate the dumping of drained fuel into the atmosphere or onto the ground. An analogous control method is defined later under ground operations modifications which would serve the same function, but would consist of ground-based auxiliary equipment.

Divided Fuel Supply System

This control method consists of a modification of the fuel supply system to allow some fraction of the fuel nozzles to be shut down during low power operation. The modification would result in increased fuel flow through the remaining fuel nozzles, thereby increasing the local fuel-air ratio in the combustion region. This increased fuel-air ratio should result in more efficient combustion and reduced CO and THC emissions during idle and taxi operations. This control method is considered to be feasible for all turbine engines and is used currently in some small engines. In engines with can or canannular combustors, operations with all fuel nozzles probably would be required at start-up to achieve ignition in all cans. However, the control method could be applied immediately after ignition.

Water Injection

Water injection is used in many turbine engines to allow engine power output to be increased without increasing turbine inlet temperatures. Use of the method in civil aircraft generally is limited to take-off operations on hot days. No data have been published on the effect of existing water injection systems on exhaust emissions from aircraft engines. However, steam injection has been shown to result in substantial reductions in NOx emissions (Ref 14). With current aircraft injection systems, water is introduced well upstream of the combustor and probably is vaporized before entering the combustion zone. Therefore, its effect can be expected to be the same as steam injection.

It is assumed that water injection for NOx control would be accomplished by means of injection systems similar to those in current use. Water injection would be used during take-off and climb-out operations with an injection rate approximately equal to the engine fuel consumption rate. In addition to the installation of the injection system, the aircraft would require a supply of demineralized water. It is possible that regular use of water injection would reduce combustor service life due to increased corrosion rates.

Water injection is the only control method which has been defined which would achieve substantial reductions in NOx emissions from existing engines. It offers the potential advantage of discretionary usage. That is, use of the method could be limited to situations where NOx control is required to improve local air quality.

Modify Compressor Air Bleed Rate

This control method consists of increasing the bleed air rate from the compressor during low power operation. Its effect would be to reduce the flow of air through the combustion chamber and increase the fuel-air ratio. As with control method t4 (divided fuel supply), this change would produce more efficient combustor operation and reduced CO and THC emissions. Maximum air bleed rates for current engines are approximately 5 to 10 per cent of total airflow. In defining this control method, it is assumed that this rate can be increased to 20 per cent at idle by modification of the flow passages and bleed valves at the compressor exit. These modifications must be achieved within the geometric constraints of the engine cowling, and bleed air must be exhausted without creating excessive noise. With these constraints, a bleed rate of 20 per cent may not be feasible. However, some increase over current rates is likely.

Variable-Geometry Combustion Chamber

Variable geometry in combustor design is not a new concept. This feature has been employed in experimental combustors for many years (Ref 15). It has not been used in practice since the added complexity has not been justifiable on the basis of improved combustor performance. The function of variable geometry is to provide control of the fraction of the total flow which enters the combustion zone. With such control, the combustion zone fuel-air ratio can be maintained at a value corresponding to efficient combustion performance at all operating conditions. This feature alone will provide substantial reductions of CO and THC emissions at low power. With the addition of an advanced type of fuel injection system which provides a high degree of premixing of fuel and air, substantial reductions of NOx and particulate emissions also can be achieved (Ref 16).

A variable-geometry combustor increases the complexity of the engine and its control system, and therefore, would increase the cost of developing and manufacturing the engine. It is possible that a combustor with movable parts also will have a shorter service life than fixed geometry combustors.

Staged Injection Combustor

Staged injection is a concept wherein combustion occurs in discrete steps in the flow of air through the combustion chamber. The concept can take a variety of forms. However, the most likely form for improved emission control would consist of dual combustion zones arranged in series with independent fuel injection in each zone. The first zone would serve primarily as a pilot combustor and would operate continuously at a fuel-air ratio providing very efficient combustion. The rate of fuel injection in the second zone would vary widely to provide variation of engine power. Fuel would be introduced by means of advanced fuel injection concepts which provide a high degree of premixing with the inlet air.

The added flexibility of dual combustion zones and fuel injection systems would be used to achieve the same results as with variable geometry. Performance evaluations of staged injection combustors have not been published, but it is reasonable to expect substantial reductions in all emissions with the use of this concept. The approach is advantageous in that no movable combustor parts are required. However, a staged injection combustor may be larger in size than a conventional combustor for the same engine.

Piston Engine Modifications

Control methods considered feasible for aircraft piston engines are listed in Table 11. These methods include most approaches to control of carbon monoxide (CO) and total hydrocarbon (THC) emissions which have been developed for automotive engines. Control methods for nitrogen oxide (NOx) emissions are not included since the fuel-rich operating conditions of aircraft piston engines automatically result in low NOx emission rates (Ref 1). NOx emission control may be required, however, in conjunction with any attempt to reduce CO and THC emissions by changing engine operating conditions.

Eight piston engine control methods are listed, including direct-flame afterburners and water injection which are not being considered currently for automotive engines. Afterburners are included here since they might be used to advantage by utilizing the high velocity airflow around the aircraft. Also, the feasibility of adapting other methods may be less for aircraft than for automobiles.

The piston engine emission control methods were identified and evaluated through reviews of published evaluations of these methods. Of the methods identified, all are considered applicable to existing engines except for any attempt at redesign of the basic engine or its control systems. The methods are described briefly below. More detailed descriptions of these methods can be found in References 17 and 18.

Simple Air Injection

Simple air injection consists of controlled amounts of air injection at the exhaust ports of each engine cylinder. The method results in modest reductions in CO and THC emissions.

Thermal Reactors

The thermal reactor is an extension of the air injection concept. An insulated chamber is mounted in the exhaust system into which air is injected. Improved mixing of exhaust gases and air and increased residence time provide substantial reductions in CO and THC emissions without increasing NOx emissions. Thermal reactors do not function effectively until they reach their steady operating temperatures. Thus, they are not effective at reducing emissions during engine start-up.

Catalytic Reactors

Catalytic reactors for control of CO and THC emissions function in a manner similar to thermal reactors. Additional air is injected and mixed with exhaust gases in a chamber mounted in the exhaust system. Oxidation of CO and THC is induced by catalyst beds through which the gases flow so that the reactor operates at a lower temperature than thermal reactors. Like the thermal reactor, the catalytic reactor does not function until it reaches its normal operating temperature.

Direct-Flame Afterburner

A direct-flame afterburner is a thermal reactor with both air and additional fuel injected to maintain the temperatures required for CO and THC oxidation. The use of additional fuel for temperature control allows the afterburner to be installed at the end of the exhaust stack where air could be induced from the propeller stream. Air induced in this manner would eliminate the necessity for an auxiliary air pump. An afterburner would, however, require a separate fuel supply system.

Afterburner effectiveness would be comparable to thermal reactor performance and it would be effective immediately upon start-up. Thus, its over-all performance would exceed that of the thermal reactor over a complete operating cycle.

Water Injection

Water injection provides a means for operating an aircraft piston engine at leaner fuel-air ratios so that CO and THC emissions would be reduced. Water injection would allow this change without increasing engine heating or NOx emissions. The function which would be served by water injection is now provided by the injection of excess fuel. The rich fuel-air ratios resulting from this practice are responsible for the high CO and THC emission rates from aircraft piston engines (Refs 1 and 3).

With this control method, water would be injected at controlled rates into the engine inlet manifold. A separate fluid storage and control system would be required as well as a supply of demineralized water. The regular use of water injection could be expected to result in increased corrosion rates of engine components.

Positive Crankcase Ventilation

Positive crankcase ventialtion (PCV) is in nearly universal use in new automobile engines. It consists of a connecting line between the engine crankcase and the air intake with a valve to control the flow rate in the line. The system creates a flow of air through the crankcase which flushes blow-by gases from the cylinders and carries them into the air intake. CO and THC emissions in the blow-by gases are oxidized during the normal cylinder combustion process or by an auxiliary control method in the exhaust system.

PCV systems would not be effective with aircraft engines unless they were adjusted to operate at leaner fuel-air ratios. With their present operating conditions, no excess oxygen is available in the engine cylinder to oxidize blow-by emissions. Thus, the PCV system is not considered to be an effective emission control method for aircraft piston engines unless it is combined with another method for CO and THC emission control. When combined with another control method such as a thermal reactor, PCV will increase the effectiveness of THC emission control substantially since the other control methods do not affect blow-by emissions.

Evaporative Emission Controls

Control systems are being developed currently to reduce THC emissions due to evaporation from fuel supply systems. These control systems make use of a variety of concepts and components, but generally accomplish emission control by collecting evaporated fuel while the engine is shut down and feeding the collected fuel to the engine when it is started.

The magnitude of evaporative emissions from piston-engine aircraft is not known, and the adaptability of automotive control methods to aircraft also is unknown. It can only be stated qualitatively that THC emissions probably occur due to evaporation and that they are amenable to some degree of control by methods which exist for automobiles.

Engine Redesign

During the past several years, several minor design changes have been made with automobile engines to reduce emission rates without the addition of auxiliary control devices. These changes include modifications in combustion chamber geometry, valve and spark timing, and fuel-air ratios. Other changes which might also be made to reduce emissions include changes in compression ratio and cylinder wall temperatures. Some degree of emission control can be achieved by such changes in aircraft piston engines. However, these changes also are likely to increase engine operating temperature, reduce power output, and increase NOx emissions. Thus, the degree of CO and THC emission control attainable by engine redesign is considered to be modest, unless other control methods are used in conjunction with design changes.

Fuel Modifications

Modifications of aircraft fuels can be considered for control of emissions of lead, SO_2, and visible smoke. These modifications consist of removal of fuel impurities, the reduction of currently used additives, or the introduction of new additives. It is recognized that emissions of reactive hydrocarbons and aldehydes are related to fuel composition. However, these relationships are not sufficiently well defined to provide bases for emission control methods.

Fuel modifications are discussed briefly below, but have not been considered in the detailed analyses of emission control effectiveness and costs which follow. With the exception of lead emission control, modifications of fuels are not considered to be feasible methods of emission control. The effects and costs of lead reduction are well-documented elsewhere and need not be evaluated in detail in this program.

Lead Emission Control

Lead additives are contained only in aviation gasolines used by aircraft piston engines. Turbine engine fuels do not contain lead additives. Low-lead or lead-free gasolines similar to those which are available for automobile engines in limited quantities, could be used in aircraft engines. However, a higher lead content may be required for aircraft engines because of the relatively high octane requirements of certain engines. Low-lead gasolines are more costly than conventional leaded gasolines by about 10 per cent. A more serious problem, however, is the incidence of valve failure resulting from the use of low-lead gasoline. Thus, a reduction in lead may result in increased engine maintenance costs as well as fuel costs. The degree of emission control achievable is, of course, directly proportional to the reduction in lead content of the fuel.

SO_2 Emission Control

Both aircraft piston-engine and turbine-engine fuels contain sulfur as an impurity. The sulfur content is highest in the heavier turbine engine fuels. However, the sulfur content of all aviation fuels, typically less than 0.05 per cent, is far below that of liquid petroleum fuels used for heat or power generation in stationary combustion systems. Reduction of the sulfur content of aviation fuels below their current levels would be very costly.

Smoke Emission Control

Various materials have been found to reduce smoke emission from turbine engines when added to fuels in small quantities (Ref 1). Most of these materials are metal compounds which have adverse effects on engine components and produce new emission species with unknown, but unattractive, characteristics. Thus, additives for smoke control are not considered to be desirable for regular use in aircraft engines at the present time. It is possible, however, that further research will produce smoke-control additives which are free of these undesirable effects.

Control Method Effectiveness

The effectiveness of each of the control methods listed in Tables 10 and 11 has been estimated and the results are listed in Tables 12 and 14. Estimates are based upon demonstrated performance in a few cases. However, in most instances, no direct experience has been obtained with these control methods on aircraft engines. Therefore, to a large extent, the effectiveness estimates are based on theoretical analyses of engine performance with the changes in operating conditions associated with the control methods. The bases for these estimates are indicated in the tables.

Effectiveness of each control method has been rated according to a scale of the degree of emission reduction attainable. The degree of reduction is expressed on an "order of magnitude" basis where, in this case, an order of magnitude is defined as a reduction by a factor of two. Considering the uncertainties involved in the application of these control methods to aircraft engines, effectiveness estimates cannot be made more accurately than within a factor of two. Therefore, this approach is considered to be valid and it offers a systematic method of classifying the effectiveness of various engine and control method combinations. The effectiveness rating scale resulting from this approach is as follows:

Order of Effectiveness	Per Cent Reduction Attainable	Fraction of Emission Rate Remaining
First	50	0.5
Second	75	0.25
Third	90 (Rounded)	0.1

Emission control effectiveness is indicated in the tables by one of these orders of effectiveness for each control method and pollutant for which a significant degree of control would be expected. Pollutants for which little or no control would be expected are not listed. Effectiveness is indicated separately for each engine class.

No estimates have been made for control of reactive hydrocarbons or aldehydes since control methods applicable to these emissions have not been identified. It is reasonable to expect some reductions in these emissions along with reductions in THC emissions.

Emission control effectiveness for turbine engines is based upon reductions attainable from "best current" emission rates. These rates are defined as those attainable through control method t1-- minor combustor redesign. The best current rates were taken from the compilation of emission data shown in Figures 1 through 4. It is assumed that all engines in each class could be modified to achieve these best rates. The values of these rates are listed in Table 12A. These best rates are not the lowest rates indicated for each engine class, but are rates near the low end of each data set which appear to be realistically attainable. The use of the "best rate" basis is necessary to allow effectiveness estimates to be made by engine class. Because of the wide variations in actual emission rates for turbine engines, the use of average rates as a basis for an effectiveness analysis would be less meaningful.

Effectiveness estimates for piston engines are based on reductions from current uncontrolled rates listed in Table 13. Emission rates from piston engines do not vary widely, so that control effectiveness can be based on average rates for existing engines.

The effectiveness estimates shown in Tables 12 and 14 are based in most cases on the application of individual control methods with the engine otherwise unchanged. Exceptions are made in the case of methods t2, t4, t5, and t6 for which it is assumed that method t1 has already been utilized to achieve "best current emission rates". Method p6 (PCV) also is an exception in that it is only considered to be useful in combination with method p1, p2, p3, p4, or p5.

From the effectiveness estimates, the following general statements can be made with regard to the various emissions:

1. Minor combustor modifications (t1) would result in modest reductions in all emissions, and would eliminate all or most visible smoke emission.
2. Other turbine engine modifications would provide further reductions in particulates (t2), NOx (t5), and low power emissions of CO and THC (t4 and t6).
3. Future turbine engines with combustors of advanced design will have low rates of emission for all pollutant classes and probably will not require additional control methods.

4. Various degrees of control of CO and THC emissions can be achieved for aircraft piston engines by modifying engine design characteristics, or by installing auxiliary control devices.

Any of the modifications defined for existing turbine engines (t1 through t6) could be combined to achieve increased emission control effectiveness, with the exception of methods t4 and t6. These two methods are mutually exclusive. Piston engine modifications p1 through p5 are designed to serve the same function and, thus, are mutually exclusive. All of the others could be combined with any of p1 through p5 to achieve increased emission control effectiveness.

IMPLEMENTATION COSTS AND TIMES OF CONTROL METHODS: ENGINE MODIFICATIONS

Included among the objectives of this program is an evaluation of the cost and time requirements associated with the application of emission control methods to aircraft engines. The program is concerned with engines in current use and engines which will be in service during the next 10 years. The evaluation of current engines is based upon the application of control techniques to specific existing engines, whereas the evaluation of future engines is on a different basis, involving future engine characteristics and populations. The purpose of this section is to present the results of the analysis in terms of cost and time requirements associated with the application of several specific emission control methods.

Engine Classification and Control Method Definition

The current turbine and piston engine population, classified into three turbine classes and one piston class, was presented previously in Tables 7 and 8, respectively. These tables list engines by "family", meaning that only the basic engine model number is considered, such as CF6 or JT9D. The table also identifies the engine manufacturer, the engine type, the engine thrust or equivalent power level, the turbine engine combustor type, the number of engines in current use, the maximum production capacity for each engine, where available, and the aircraft class in which the engine is used for correlation with the data provided in Tables 1 through 5. Note that the total number of turbine and piston engines listed in Tables 7 and 8 in current use are further broken down into air carrier, general aviation and military engines.

The emission control methods applicable to both turbine and piston engines are listed in Tables 10 and 11, respectively. In each table, the control methods are subdivided into categories applicable to current engine (retrofitting) and to future engines. In general, it has been concluded that emission control methods appropriate for future engines cannot be incorporated into current engines. Since the incorporation of these "future" engine emission control methods would be an intrinsic part of the "future" engine design process, the analysis of the cost and time involved is not compatible with the analysis conducted on current engines. Hence, future engine emission control is discussed separately in this section, following the initial discussion of the current engine analysis.

Cost and Time Analysis Procedures

An analysis of the cost and time involved in the application of various emission control methods to current engines was conducted, using the procedures applied to the JT8D engine "family" in Reference 2, as a basis. Costs and times were established for both turbine and piston engines for two general categories, which are best described as "Development" and "Implementation" costs and times, the elements of which are described in detail below.

For the case of the turbine engines, it should be recalled that three classes of engines has been suggested in Table 7, based upon thrust level ranges. For each class or thrust range, a typical or "baseline" engine was selected for the cost analysis, with the selection criteria being generally based upon population. The analysis procedure is illustrated in the tables provided which include a "sample calcuation" of both the development and implementation costs and time for class T2 engines for which the JT8D is the "baseline" engine. A similar procedure is followed with sample calculations provided, for the piston engines, although no specific "baseline" engine was identified, since only one class of engine exists and the size or power range is much narrower for the piston engines as compared to the turbine engines.

The turbine and piston engine sample calculations are described in the following paragraphs. It should be noted that the explanatory paragraphs apply generally to one engine class only such as the class T2 turbines for which the JT8D is used as a baseline engine. In order to arrive at costs for other turbine engine classes, a scaling factor is used which is explained in later paragraphs. The process can be visualized best by a study of Figures 6 through 10.

"Development" Cost and Time Analysis

The term "Development", as used herein implies the "one-time" costs and times associated with the evaluation and refinement by testing of a given emission control method for a specific engine family. It also includes the tool design and procurement costs and times required to introduce the given control method into the production schedule for production engines, if applicable, and with the overhaul schedule for retrofitted engines. The "development" cost and time elements which were treated for each control method are described below, in the order listed in Tables 15 and 17.

Engineering Development Cost

This cost consists of the manpower costs associated with a "team" of engineers and draftsmen who perform the necessary analysis and design calculations required for a given control method and produce sets of drawings and test hardware ready for testing.

Engineering Development Time

This time covers the period from the initial analysis until hardware is ready for testing.

Testing Cost

This cost consists of the manpower costs associated with a "team" of engineers and technicians who perform the tasks of assembly, installation, testing, data analysis, and disassembly in that order on various sets of test hardware supplied in original and modified form until the testing of the final, refined emission control system is completed. Testing facilities are assumed to exist. The cost of operating the test facilities is included.

Testing Time

This time covers the period from the receipt of initial hardware ready for test through the analysis of the test results of the final, refined emissions control system.

Tool Design Cost

This cost consists of the manpower costs associated with a team of engineers and draftsmen who produce a set of drawings, including tooling, required to fabricate a complete emission control system.

Tool Design Time

This time covers the period from completion of final testing until completion of final drawings, ready for production.

Tool Procurement Cost

This cost assumes special tooling and/or equipment is required in order for the given emission control method to be produced at a rate equal to that required. It is recognized that the production rate and resulting cost depends upon the number of engines in use and the current or projected engine production rate.

Tool Procurement Time

This time covers the period from the completion of final drawings until all tooling and/or equipment required is available for initiation of production of the specific engine control system components.

Total Development Cost

This cost is initially found as the cost per engine family (JT8D) and is the summation of all the cost elements previously listed, including engineering development, testing, tooling design, and tooling procurement. Total development costs per engine family were assumed to vary among the several emission control methods considered, but were assumed to be equal for a given control method applied to various engine families in the same engine class. The number of engine families in a given class is used to get the final development cost for that class. It is recognized that the cost of the test hardware and test facility operating costs will vary with engine size (or class) but differences are assumed negligible for the analysis.

Total Development Time

This time is the summation of all the time elements previously listed, as above.

Total development times were assumed to vary among the several emission control methods considered, but were assumed to be equal for a given control method applied to various engine families in the same engine class and also in different engine classes.

A summary of these costs and times for both turbine and piston engines is presented in Tables 15 through 18 for the various appropriate emission control methods.

Implementation (Retrofitting) Cost and Time Analysis

The term "implementation cost" as used herein applies to those cost elements involved in the incorporation of a developed control system into a specific engine which is currently "in-use". This implies a retrofit operation. The cost can be expressed as a total cost per engine or as a total cost when multiplied by the total number of engines affected. The latter value is assumed to be the total implementation cost, unless otherwise specified. The implementation analysis assumes that control systems will be incorporated on an "overhaul" basis, as defined in Reference 2, and two and one-half years is assumed for an "implementation time" for the JT8D, used as a baseline engine in the sample calculation.

The "implementation" cost and time elements which were treated for each control method are described below. As with the development costs and time calculations, the procedures for calculating implementation costs and times are illustrated by means of tables which contain sample calculations for the same class T2 engines for which the JT8D is still the "baseline" engine. The sample calculations are found in Tables 19 through 22 and again show results for only the one class of T2 engines. The scaling factor previously mentioned and explained later is used to obtain costs for other engine classes, where applicable. Since there is only one piston engine class, no scaling relationship is required for piston engines. Again, a study of Figures 6 through 10 should clarify the procedures used.

Lost Service Life Cost Per Engine

Since "implementation" was assumed to be on an overhaul basis, as defined in Reference 2, the cost of replacement would include the cost associated with the remaining service life of the original combustors. On the average, the unused service life was assumed to be 2500 hours for the JT8D, or one-fourth the total combustor life. The corresponding cost would be one-fourth of the original cost of the combustors or approximately \$2500 per engine in the sample case of the JT8D.

Initial Additional Installation Cost Per Engine

This cost includes the additional manpower and equipment costs, if any, per engine involved in the installation of a given emission control system into a specific engine. For example, it was estimated that the cost of installing a "minor" combustion chamber modification (control method t_1) into a JT8D engine would be \$2000, per Reference 2.

Continuing Additional Cost Per Engine Per Year

This cost is associated with the increased cost of combustion system components and their (probable) reduced service life. As an example, this cost for a "minor" combustion chamber modification on the JT8D engine was calculated to be \$2500 per engine per year[*], assuming a service life of 5000 hours or two years of service reduced from the current assumed combustor service life of 10,000 hours or 4 years of service. The increased list price of the combustion chamber components was estimated to be \$11,000 compared to a current approximate price of \$10,500. Actual prices vary as a function of the quantity of the combustors ordered by an operator and also as a function of the annual inflationary

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[*] Assuming that on the average, aircraft operators pay 87 per cent of list price, increased yearly cost is

$$\text{cost/engine} = 0.87\left[\frac{\text{new cost/set}}{\text{service life}} - \frac{\text{old cost/set}}{\text{service life}}\right]$$

$$= 0.87\left[\frac{\$11{,}000}{2\text{ years}} - \frac{\$10{,}500}{4\text{ years}}\right] = \$2500\text{ per year}$$

spiral, neither of which effects has been specifically included in this analysis. The assumed reduction in service life for modified combustors is consistent with the conclusions of Reference 2, based on aircraft operators experience. Although modified combustor service life has not been established yet, even for the JT8D, it seems reasonable that any modifications to a highly developed component such as the combustor will introduce some initial difficulties, the end result of which is a reduction in service life or a loss in reliability. The solution to the problem is another phase of development, not included elsewhere in this analysis. The validity of the assumed values for reduced service life is unknown at this time but the need to include this cost element in the analysis certainly seems valid.

Total Implementation Cost Per Engine

This cost is the summation of the three previously listed cost elements. Note that the units of the "continuing additional cost per engine per year" requires that some time span must be introduced in order that the units be consistent with the other cost elements and the resulting summation legitimate. Since the period of interest for this program has been stated to be the 10 year span from 1970 to 1980, 10 years has been assumed for a time span, henceforth referred to as "engine life". This 10 year span has no necessary relationship to the actual useful life of either turbine or piston engines. A cost/time model was established for purposes of consistency, as shown in Figure 5, which assumes a finite engine life as explained above and a time between overhauls (TBO). In the sample baseline case of the JT8D engine, 5000 hours or 2 1/2 years was assumed for the time between overhauls (TBO) and an engine life of 10 years was also assumed. This results in a total implementation cost per engine of $35,500 for the 10 year assumed life of the engine. Similar assumptions were made for the piston engine analysis, as shown in Figure 5.

Total Implementation Cost

This total cost is established from the previously described implementation cost per engine by multiplying that unit cost by the number of engines in the given class of turbine engines. The number of turbine Class T2 engines is projected to be 35,874 which means that the total implementation cost will be 35,874 x $35,500 per engine or 1275 million dollars for that class of engines for the assumed 10 year engine life and 2 1/2 year assumed value for TBO. Sample calculations of total implementations costs for both turbine and piston engines are provided in Tables 19 and 21.

Total Implementation Time

As previously stated, implementation was assumed to be on an overhaul basis which results in an average value of two and one-half years to completely convert all engines in a given family of turbine engines in use.

A summary of the implementation costs and times for both turbine and piston engines is presented in Tables 19 through 21 for the various appropriate emission control methods. The principal guidance for distributing costs and times among the various emission control methods, relative to the initial t_1 case presented here and in Reference 2 for the JT8D, was obtained in References 20 through 24.

Total Development and Implementation Cost and Time Analysis

Having established the costs and times associated with the sample case of the JT8D engine, and the T2 engine class, of which it is a member, the analysis procedure used to obtain cost and time data for the entire aircraft engine population is illustrated graphically in Figure 6. It can be seen from Table 7 that the JT8D is a Class T2 turbine engine and that there are 20 engine "families" in that class which also includes a total number of 35,874 engines. Assuming that the JT8D engine family is representative of all engine families in the Class T2 turbine group, total Class T2 turbine engine development costs are obtained by multiplying the JT8D baseline development cost by 20 as in Table 15 and the total Class T2 turbine engine impelmentation cost is obtained by multiplying the JT8D baseline total impelmentation cost per engine by 35,874, as in Table 19. It is assumed that both development and implementation times as a function of emission control methods for the JT8D engine are equal for all other engine families in the T2 class and in the other turbine classes. Similar assumptions are made for the piston engine families, as tabulated in Table 8.

Extending the results of the JT8D baseline case to all "families" in the Class T2 turbine group results in a simple table, as illustrated in Figure 6, of total cost and total time for all Class T2 turbine engines, for each emission control method, covering the period from initial engineering development through the conversion of the last engine "currently" in use at the end of the overhaul period assumed.

Cost Scaling Factor

Using the analysis described above, a table of total costs and total times for one class (T2) of turbine engines has been explained. To arrive at comparable tables for other classes of engines, as suggested in Figure 6, it is necessary to repeat the analysis for other "baseline" engine families in the other engine classes or to establish a scaling relationship which can be used to obtain tables of costs and times for the other engine classes. The latter approach has been selected.

Technical Scaling Parameter

Considerable effort has been devoted to trying to correlate aircraft turbine engine cost with technology, which includes both size and performance. An example of this effort is provided in Reference 25. Since both size and performance are involved in the turbine engine classification system adopted in this analysis, the combination technical parameter presented in Reference 25 seemed appropriate and in fact provides a reasonable scaling relation as shown in Table 23 and Figure 11.

Final Scaling Parameter

A cost variation proportional to the square root of engine thrust (or equivalent horsepower) was suggested and investigated with results also shown in Table 23 and Figure 11. The simplicity of this scaling parameter is appealing and since it appears to correlate very well with the technical scaling parameter, its use was adopted for this analysis.

Final Scaling Factor

As suggested in Figure 6, simple tables of costs and times are required for all three turbine engine classes, of which only the Class T2 engines have been explained, using the JT8D engine as a baseline example. Baseline engines for the other two turbine classes were selected for scaling purposes, based generally on population, as shown in Table 7 and listed below:

Turbine Class	Baseline Engine
T1	T53
T2	JT8D
T3	TF39

Calculation of both the technical and final scaling parameters and normalization of the parameters relative to the JT8D baseline engine case, yields normalized final scaling factors as shown in Table 23. The scaling factors used were 0.35, 1.00, and 1.64 for the Class T1, T2, and T3 turbine engine classes, respectively. These factors are applied to the total implementation cost per engine only, based on the assumption that development costs are essentially independent of turbine engine class. Again, reference to Figures 6 through 10 should aid in understanding the procedures used.

Final Cost and Time Results for Current Engines in Service

The final results of this analysis are presented in Tables 24 through 27 for both turbine and piston engines now in service. The tabulation includes the engine classification, the baseline engine assumed, the emission control method, the number of engine families in a given engine class, the number of total engines in a given engine class, the total development and implementation cost for a given engine class, and the total development and implementation time for a given engine class. The latter two values of total cost and total time are presented for engine classes as a function of the several control methods selected. Costs are further broken down to show air carrier, general aviation, civil aviation and military aviation costs in addition to total costs for both turbine and piston engines. The result of Tables 24 and 25 are shown graphically in Figures 6 through 10.

Total Implementation Cost/Engine for "Production" Engines

The analysis and results presented thus far, for both turbine and piston engines, apply to engine models and populations now in existence and assume emission controls will be developed and implemented on an overhaul basis, as previously explained. Certain of these engines will still be in production at the end of the development period and the "implementation" costs associated with production engines must be treated differently from engines currently in service and requiring a retrofit of the developed control systems. Implementation costs were analyzed for production engines on a basis similar to that presented previously. However, the cost associated with the useful life remaining in a discarded combustor system cannot be included and it is assumed that the additional installation cost, if any exists, associated with the new emission control system will certainly be lower than that for a retrofitted engine now in service. The continuing additional cost per engine per year was assumed to be the same as for a retrofitted engine and 10 years was again used as a value for "engine life" in order to have the cost results on a comparable basis. Since future engine production values are unknown, results are presented on the basis of a 10 year implementation cost per engine. A "sample calculation" for both turbine and piston engines is presented in Tables 28 and 29, respectively. These results can be compared with those presented in Tables 19 and 21 and are somewhat lower, which seems reasonable. Final results for all classes of engines, including the three turbine classes, is presented in Table 30. As indicated, the same scaling factors previously presented have been used for the turbine engine classes.

Control Methods Applicable to Future Engines

Intensified interest in controlling emissions from aircraft turbine engines has already stimulated research on combustors for the next engine generation. Current combustor design practices are recognized to offer only limited emission reduction. In late 1968, the National Academy of Engineering recommended government support for the development of combustors using variable geometry and air atomization fuel injectors (Ref 29).

The advantage lies in controlling local combustion zone fuel-air ratios over the entire operating range. This departure from current design practice does not represent a new concept, but rather a method for achieving low emissions from the current design concept.

A more radical suggestion for reducing emissions in the next generation of engines is a new design concept - viz. the use of staged-combustion (Ref 16). The idea is to introduce a series of separate combustion zones with independently controlled fuel injection in each zone. Air atomization fuel injection would be used in all zones. Again the objective is to maintain control of local fuel-air ratios over a wide operating range of the combustor. Several fluid dynamic and combustion problems must be solved before staged-combustion becomes workable. The only serious development problems in the case of variable geometry center on the added mechanical and control system complexity.

Reduced emissions is not the only factor promoting development of more complicated combustors for the next engine generation. Better control of the mixture can also provide more uniform turbine inlet temperature profiles. As turbine inlet temperatures increase with the next generation; more uniform profiles over the entire flight map may be a definite requirement for practical thermomechanical design of cooled turbines. The feasibility of advanced combustors for reduced emissions should be assessed with this in mind.

Basis for the Cost and Time Estimates

Either of the control methods applicable to future engines will require development of new combustors. In the past, the development of advanced component design concepts has to a large extent been supported by the federal government -- by NASA or by the military. Indeed, the USAF ATEGG type program might be ideal for developing variable geometry or staged-injection combustors. Even after the technology is established, however, each new engine requires separate additional development of its components. The total development cost for an advanced combustor is thus a somewhat misleading figure when assessing the practicality of emission control methods. New combustors will be developed regardless of emission requirements.

The number of interest is rather the incremental cost which will result if emission criteria necessitate variable geometry or staged-combustion. The cost and time for developing demonstrator combustors using variable geometry or staged-combustion are estimated below. Also estimated are the fractions of the total cost and time which will result from emissions control rather than from normal evolution of advanced combustors for new engines. The development costs and times are broken down into design and testing categories in the same manner as in the preceding treatment of control methods for current engines. An additional category, pertaining to incorporation of prototype combustors into engines covers the effort required to integrate the combustor with other components.

There is a second approach to assessing the cost of emission control in future engines - viz. the incremental increase in engine purchase price which results from more complicated combustors. Hardware and assembly costs will increase with added design complexity. Total engine costs vary radically with parameters unrelated to combustion (e.g., airflow and weight). For this reason, the incremental costs of emission control in future engines are best defined in terms of the percentage of the total engine cost associated with the combustor. In the JT8D the combustor represents roughly 4.5 per cent of the engine cost (from Ref 2, assuming 11K for the combustor and 250K for the engine). The combustor costs as a per cent of the engine price are included in Table 31, both for variable geometry and for staged-combustion.

In sum, then, three cost numbers are provided: advanced prototype combustor development cost; fraction of development cost associated with emission control; and fraction of engine purchase price associated with different combustor concepts. All raw cost numbers assume an engine size essentially the same as the JT8D.

Discussion of Results

The various cost and time numbers for conventional combustors, for combustors incorporating variable geometry, and for staged-injection combustors are summarized in Table 31. The discussion below examines the advantages and disadvantages of each emission control method for future engines.

Variable Geometry Combustors

Since variable geometry combustors using air atomization fuel injectors were recommended in 1968 by the National Academy of Engineering, it seems safe to assume that development efforts are already underway. Air atomization fuel injectors are not expected to cost more than conventional injectors once production levels are reached (Ref 30). The major cost lies rather in the added mechanical complexity of a combustor with hot moving parts and in the need for an actuation and control system to vary the geometry during engine operation. Any gains in engine performance or in turbine weight (as a result of better inlet temperature profile) will at least be offset by the additional weight of the variable geometry combustor. The incremental cost and time associated with introducing this type of combustor in future engines consists primarily of the development and manufacturing problem of varying the geometry.

As indicated in Table 31, the design effort required by variable geometry is estimated to be twice that of a fixed geometry combustor. This figure assumes a 20 per cent increase in fluid design effort, a 100 per cent increase in mechanical design, and a control design effort comparable to the customary mechanical design effort. The increased cost of prototype hardware represents first, higher tolerances on critical varying geometry parts and second, additional actuation and control components. The increased test costs result first from time spent optimizing the geometry at various operating conditions and second from anticipated mechanical problems in actuating geometry changes during operation. The additional engineering effort required to incorporate a prototype variable geometry combustor into an engine results from added control system complexity.

The purchase cost of a variable geometry combustor using air atomization fuel injectors is expected to be about twice that of a comparable fixed geometry combustor. The combustor hardware cost should increase by 50 per cent, and the rest of the additional cost stems from the actuation and control hardware.

Since no new combustion concepts are involved with the variable geometry combustor, the essential engineering problem is to design an actuation and control system which is compatible with the rest of the engine. The only other issue is assuming adequate life of more critically designed parts. The development time estimated for a prototype combustor of this type reflects these considerations.

Staged-Injection Combustors

Staged-combustion is a more radical departure from current combustor design practice. The problem with variable geometry is to implement a concept which will surely work from a combustor performance standpoint. The problem with staged-injection is to develop and to prove the concept itself. Several combustor performance difficulties are anticipated. These are best understood by describing the concept in slightly more detail.

One approach to staged-injection uses two air atomization injectors where one is used now. One of these fuels a pilot burner, and the other introduces the major part of the design fuel flow into a prechamber. Fuel is premixed and vaporized in this prechamber before entering the combustor proper. A serious technical problem is the danger of flash-back into the prechamber. High gas velocities are needed in the prechamber for mixing, and a considerable pressure drop is needed between the prechamber and combustor proper to prevent flash-back. Careful fluid dynamic design of a more complicated network is needed if pressure losses are to be acceptable. On the other hand, the flexibility provided by a pair of injectors should improve combustor flame stability.

The costs shown in Table 31 for the staged-injection combustor reflect the need for technological development of the concept. The much larger engineering design and test effort indicated will be devoted to combustor rig exploratory development programs. Different arrangements of the prechamber and pilot will require examination with particular attention to a fluid dynamic design which will provide adequate prechamber mixing, low pressure losses, and no flash-back problems. Once an acceptable prototype staged-injection combustor is obtained, it can more readily and less expensively be incorporated into an engine as compared to the variable geometry combustor. No actuation or complicated control system is needed -

only two fuel lines with separate controls of the type currently used in zoned afterburners. Compressor diffuser designs will, however, doubtlessly require revision.

The production cost of staged-combustion is greater than that of conventional designs first, because twice as many fuel injectors are needed and second, because the structural design must provide a more complicated flow path. However, staged-combustion, once developed, should offer a noticeable cost savings versus variable geometry.

EFFECTIVENESS OF CONTROL METHODS: GROUND OPERATIONS MODIFICATIONS

Introduction

This section of the report examines how effective seven suggested ground operations changes would be in reducing aircraft emissions. The next section will evaluate the cost and time for implementing the changes. The suggested changes are:

1. Increase engine idle RPM.
2. Use a minimal number of engines for taxi operations and increase the idle RPM of the engines used.
3. Minimize unnecessary engine time by a system for controlling engine start and gate departure.
4. Minimize taxi time by parking aircraft near runways and using auxiliary vehicles to transport passengers to and from the terminal.
5. Tow aircraft between runway areas and the terminal, thus eliminating the taxi mode of engine operation.
6. Provide ground-based auxiliary power supply in order to eliminate use of on-board auxiliary supply units while at the gate.
7. Provide auxiliary equipment for emptying fuel drainage reservoirs.

The effectiveness of the various changes in reducing aircraft emissions has been evaluated for a single representative airport, Los Angeles International Airport. Each of the seven changes is discussed separately below.

Control Method Effectiveness

Increase Engine Idle RPM

Two categories of turbine engine emissions, carbon monoxide and hydrocarbons, result from incomplete combustion. This occurs primarily at low engine power settings because the combustor is optimally configured for full power operation. By operating engines nearer the combustor design condition, the emission rates for CO and hydrocarbons will be reduced.

Aircraft braking power and brake wear ultimately constrain the extent to which the idle RPM can be increased. Brake overheating already occurs occasionally during ground operation.

Essentially a doubling of engine power was assumed to get a benchmark for the effectiveness of a higher idle in reducing emissions. Figure 12 approximates the relationship between power and fuel flow. Although this approximation cannot be extrapolated to zero power output, it suffices for estimating emission reduction with idle power setting change. Figures 13 and 14 give CO and hydrocarbon emission rates versus engine power setting. Figures 12 through 14 thus supply sufficient information to calculate the per cent emission reduction which results from doubling the power during aircraft idle.

Table 32 summarizes the reduction in engine emissions which results from doubling idle power output. The table also indicates the uncontrolled emission rates for each engine and the number of engines in each aircraft class (as per Ref 6). Although increasing the idle RPM reduces emissions per unit mass of fuel, increased fuel flow can offset the improvement (as in the case of hydrocarbons for Class 2 aircraft). Thus the full benefit of increased idle RPM will be realized only if not all engines are in use during ground operations.

Use Minimal Number of Engines at Increased Idle RPM

Thrust levels for taxi can be kept the same by using less than the full complement of engines, but at a higher power output level. Again the benefit will be in reducing carbon monoxide and hydrocarbon emissions which occur predominately at low power settings. Using fewer engines (and less fuel) per aircraft during ground operations will also provide an across-the-board cut in emissions. Implementation of such a change is straightforward with the sole exception of requiring fire-safety provisions at the ends of runways while departing aircraft are starting engines. At least one airline currently saves fuel by shutting down the center engine on arriving Boeing 727 aircraft, while taxiing to the gate.

The question with this method of controlling emissions at airports is how many engines are minimally needed for taxi. In the extreme it is possible to taxi with a single engine. This would provide the maximum reduction in emissions. Airline pilots do not expect that the unbalanced thrust from single engine taxi of two and four engine aircraft would be unacceptable; tests are nonetheless needed to confirm the safety of such operation as a standard procedure. A more serious factor militating against use of a single engine is the power level which would be required to resume taxi after the aircraft comes to a complete stop. With fully loaded aircraft on slight grades a 100 per cent power output from a single engine may well be necessary to resume taxi. The hazardous jet blast area would have to be extended from a current value of 150 feet to more than 400 feet. The ramifications of the increased jet blast might require substantial modification of airport taxi procedures and rules.

The extent to which the number of engines used during taxi can be reduced thus remains unclear. For this reason two sets of reduced emission numbers have been derived: one assuming single engine operation and the other, two engine operation for all commercial aircraft. Table 33 summarizes the reduction in emissions which would result if only one or two engines were operating (at a higher power level) during taxi. The reductions for the taxi mode are substantial-- particularly if single engine taxi proves to be acceptable. As discussed in the next section of the report, the savings in fuel from single engine taxi operation would surely be attractive to the airlines.

Controlled Engine Start-Up and Gate Departure

The idea is to restrict engine operation while the aircraft is on the ground to that required for taxi. The engines would be shut down at the gate. They would be started under the direction of a ground traffic control system which, among other things, would eliminate delays at the end of the runway. Such an airport ground traffic control system offers many evident advantages besides reduced emissions. However, several factors militate against its implementation. The traffic control system would have to be extremely complex if current runway utilization levels are to be maintained. Moreover, a prime reason for current delays at the end of the runway is the unavailability of gates for arriving aircraft. Airlines dispatch aircraft simply to open a gate, regardless of how soon clearance for take-off will be granted. Thus either more gates, or an intermediate parking area for departing aircraft, or more uniformly scheduled traffic levels would be necessary to implement this ground operation change. Nevertheless the orderly growth of air transport operation will doubtlessly require automated ground control to maximize airport utilization. Thus this method for reducing emissions is likely to appear increasingly practical with time.

This control method will eliminate delay mode emissions, as defined in Reference 6. In the case of Los Angeles International Airport mode times are as follows:

Mode	Time
Taxi	12 minutes
Delay	112 seconds
Maintenance	69 seconds at idle power 23 seconds at cruise power

Table 34 summarizes the aircraft emissions at Los Angeles Airport which result from each mode of ground operation. Table 35 gives the reduction of the emissions achievable by eliminating the delay mode. Carbon monoxide and hydrocarbon levels at Los Angeles Airport can be reduced by about 10 per cent. At other airports, where the delay mode represents a larger fraction of ground operation time, the reduction can be more dramatic.

Intermediate Passenger Transportation

From the point of view of emissions the use of lounges for transporting passengers to and from aircraft is attractive only if the aircraft can be parked near the runway to be used. Otherwise taxi times would not be markedly reduced from those of current operation. Ideally aircraft parking areas would be located adjacent to the runways, midway along their length. Even then the minimum taxi time will correspond to the runway length, which is not a substantial reduction over current taxi times. Moreover, practical safety requirements will increase the taxi distance since parked aircraft should not be exposed to the hazards of landing aircraft.

The general conclusion, then, is that modifying existing airports to use intermediate passenger transportation between the terminal and an aircraft staging area is unlikely to reduce aircraft emissions. The staging area at Dulles International Airport, for example, is no closer on the average to the ends of the runways than is the terminal. Introducing a staging area for each individual runway at existing airports is scarcely feasible since land shortage is already a problem at most. New airports designed to stage aircraft in the vicinity of runways might show some advantage in emissions, but the advantage would be slight. Current airport design practices already attempt to locate the terminal to minimize taxi times, commensurate with safety. Even should lounges be pollution-free, then, it is doubtful that airport emissions will improve with the mobile lounge type of operation.

Towing of Aircraft

Using auxiliary vehicles to tow aircraft around airports will dispense with aircraft emissions from the taxi mode altogether. Tow tractors would be used not only to move the aircraft clear of the gate, but then to tow the aircraft to a staging area at the end of the runway. Once clearance is granted, engines would be started at the staging area. Arriving aircraft would correspondingly shut down engines at the end of the runway and would then be towed into the gate. This type of operation has on occasion been contemplated in the past because of concern with jet blast and aircraft maneuverability (for example, by Pan American during the advent of turbojet powered commercial aircraft). The crucial disadvantage stems from a maximum speed capability of below 10 miles per hour for current tow vehicles. Since taxi times would more than double, towing aircraft around airports would require radical revisions of airport procedures and of airline schedules.

The effectiveness of towing in reducing airport emissions involves a trade-off between reduced aircraft and increased tow vehicle emissions. The trade-off is defined on the basis of kilometers travelled, assuming an aircraft taxi speed of 17.5 kilometers per hour. The values of aircraft emissions for the taxi mode (as per Ref 6) are given in Table 36. This table also indicates values for diesel powered tow vehicles obtained from Reference 31; tractors are assumed to use 17 litres per kilometer. Comparison of aircraft and tow vehicle emissions shows that even if tractors were required to do a double journey, there would be substantial reductions of carbon monoxide and hydrocarbons for most of the aircraft classes. However, NOx emissions might increase to an unacceptable level.

Table 37 shows the effect of eliminating the taxi mode emissions entirely. These values should be taken in conjunction with those of Table 36 to obtain the actual reduction from using tractors.

Use Ground-Based Auxiliary Power Equipment

There are two ways in which on-board auxiliary power units could be eliminated from use while at the gate: by using portable electric and air supplies or by equipping each gate with a centrally supplied air and electric system. The latter method is of limited practicality except possibly for a newly designed airport. Mobile units are more feasible with existing airports.

The emissions for on-board auxiliary power units are given in Table 38. They are based on those for turboprop engines at take-off conditions (Ref 6), scaled according to fuel flow rate. APU operating details have been obtained from an information sheet on the GTCP-85, published by Garrett, and from Reference 11.

Table 38 also gives the reduction in emissions which would result from eliminating the use of on-board auxiliary power units. The reduction is essentially negligible.

Use Auxiliary Equipment for Emptying Fuel Drainage Reservoirs

Fuel which collects in the engine drainage reservoirs is currently dumped as part of the take-off procedure. The emission levels associated with this operation at Los Angeles International Airport are indicated in Table 24. A demonstration is being held on August 18, 1971, of an auxiliary device which extracts and stores the fuel in the drainage reservoirs prior to aircraft take-off. This device is assumed to be 100 per cent effective from the point of view of emissions. Thus, all emissions from fuel dumping shown in Table 24 would be eliminated by implementing this ground operation control procedure.

Conclusions

Table 39 summarizes the reductions in carbon monoxide and hydrocarbon emissions which would result at Los Angeles International Airport from the seven suggested ground operation changes. The distribution of activity among aircraft classes (Ref 6) for the first two control methods has been taken as follows:

Aircraft Class	Per Cent
2	3
3	56
4	22
5	6
6	13

Pollutants other than CO and hydrocarbons appear to be less affected, although NOx emissions may increase with the use of tractors to tow aircraft. By combining minimal number of engines with controlled departure to eliminate runway delays, a substantial reduction in emissions can be achieved-- indeed a reduction at least comparable to the use of tow vehicles. Use of passenger lounges and avoidance of using on-board APU's offer no advantages in reducing emissions. The maximum effect obtainable by combining the various control methods is a reduction of emissions to about 50 per cent of their uncontrolled level for this airport, assuming two engine taxi; and to about 40 per cent, assuming single engine taxi.

IMPLEMENTATION COSTS AND TIMES OF CONTROL METHODS: GROUND OPERATIONS MODIFICATIONS

This section of the report presents estimates of the costs and times required for implementing various ground operation changes to control aircraft emissions. Constraints on feasibility which are difficult to assess in terms of time and money required for implementation are also reviewed. The effectiveness of the different ground operation changes in controlling emissions is discussed in the preceding section. Attention here is confined to the feasibility of the changes independently of their effectiveness. Seven operation changes are examined:

1. Increase engine idle RPM.
2. Use minimal engines for ground operations and increase the idle rpm of these engines.
3. Reduce unnecessary engine time by a system for controlling engine start and gate departure.
4. Reduce taxi time by parking aircraft near runways and using auxiliary vehicles to transport passengers to and from the terminal.
5. Minimize engine time by towing aircraft between runway areas and the terminal.
6. Provide ground-based auxiliary power supply in order to eliminate use of on-board auxiliary supply units while at the gate.
7. Use auxiliary equipment for emptying the fuel drainage reservoirs of each engine.

Time and cost estimates have been made for a single representative airport, Los Angeles International Airport. Costs will necessarily vary from airport to airport. The basis for making the estimates is accordingly discussed so that comparable numbers for other airports can be derived.

Basis for Estimates

The fundamental assumption made in evaluating the feasibility of the seven ground operation changes is that current operation levels at

Los Angeles International Airport remain in effect. Specifically, the peak hour load was assumed to be 120 operations involving 10,000 passengers. LA currently has 77 gates, but some of these must be paired when servicing Boeing 747 aircraft. It was therefore assumed that servicing facilities for 75 aircraft must be available at any one time-- either gates or parking facilities. Five categories of cost have been distinguished: land, construction, equipment, automation procedures, and operating. Each of these is defined and the ground rules for deriving numbers are described below. The bases for the cost estimates for each operation change are summarized in Table 40.

Additional land purchase is needed for those ground operation changes which require aircraft parking facilities other than those at the terminal. Space required for servicing varies from aircraft to aircraft, and provision for maneuver must be made. For estimation purposes, an aircraft was assumed to require an average of 1.2 acres of parking space. Land purchase prices in the vicinity of airports vary widely. A representative price of $50,000 per acre was assumed in this study, which corresponds to assessed valuation in the vicinity of Logan International Airport in Boston.

Two types of construction costs can be incurred in implementing ground operation modifications: additions or alterations to the terminal facility and additional taxiway and aircraft parking surfaces. Terminal construction costs have been estimated from the costs required to modify gates when the 747 aircraft were introduced. Surface costs have been predicated on 12 inch thick concrete, at a cost of $500,000 per acre of surfacing.

Different suggested ground operation changes require purchase of different types of new equipment. Use of tractors to tow aircraft between the terminal and the runway areas will require purchase of additional tow vehicles. At a minimum it was assumed that 80 vehicles would be needed to service 75 gates at peak load without inconvenience. Airlines currently maintain about 15 tow vehicles per twenty gates. Thus, about 25 new tractors would be needed at LA International Airport. The price of tractors varies from $20,000 for one adequate for a Boeing 727 to more than $50,000 for wide-body aircraft. An average price of $30,000 per tractor was assumed.

Use of lounges to transport passengers between the terminal and the aircraft will require purchase of lounges. At Dulles International Airport lounges costing over $200,000 can transport 110 passengers at a time. One such lounge per gate should more than suffice for peak hour loads at LA International.

Mobile auxiliary power units cost approximately $20,000 for air supply and $15,000 for electrical supply. Again the availability of one air supply and one electrical supply unit per gate should suffice for eliminating use of on-board auxiliary power units on the ground. It was assumed that currently only 50 per cent of this requirement is satisfied.

To empty at the gate the fuel which collects in the fuel drainage reservoirs will require purchase of the proper auxiliary equipment. An FAA demonstration of such a piece of equipment was held on August 18, 1971. This particular design costs $500. LA International Airport would require 75 of them-- one per gate.

In initiating a complicated ground control system, automation equipment will be needed-- in particular, a computer system with rapid information through-put capacity and with auxiliary communication equipment between aircraft and control. For estimation purposes an IBM 360-65 computer was assumed as a bench mark.

Initiation of a ground control system will also require the development and implementation of automated procedures. If computer control is to be adopted, programs will have to be developed to provide the computer with techniques for maintaining control. Programming cost consists primarily of labor at roughly $30 per man hour. Even without a computer controlled ground traffic pattern, new schedules and procedures will be needed to implement either the use of tow vehicles or passenger lounges. Again a labor cost of $30 per man hour was assumed.

Various types of operating costs were recognized. Aircraft operating expenses on the ground were estimated on the basis of fuel costs at idle for JT8D engines. The basic rule is that each engine consumes 1200 lbs/hr of fuel during idle, at a cost of $48 per hour. Operating engines at an increased idle speed, based on Boeing 727 experience, increases consumption to 1800 lbs/hr. Los Angeles International Airport had 40,000 operations during 1970. If it is assumed that the average operation involved 20 minutes of idle and taxi time and that the average "aircraft" has 2.7 engines, then the ground fuel consumption at LA alone is $17,000,000 per year. The cost savings which would result by reducing aircraft engine ground operation are accordingly of large potential. These cost savings are in part balanced by the additional costs for labor and fuel used by auxiliary vehicles. They are also likely to be balanced by the reduction in total capacity which results when ground operations require significant increases in time. The assumed incremental operating costs described below reflect these various considerations.

In estimating the time required to implement each ground operation change it was assumed that purchase of land and of equipment would encounter no unusual problems. Construction times and times required for introducing automation were estimated on the basis of current experience. Time estimates should be regarded as quite approximate since numerous social and political factors may interfere with the rapid implementation of ground operation changes.

Discussion of Results

Table 41 summarizes the costs and times required for implementing each of the seven considered ground operation changes. Money and time, however, are not the only factors affecting the feasibility of these changes. Some changes have advantages other than those associated with aircraft emission levels, while others involve disadvantages in terms of airport operation which cannot readily be assessed numerically. For this reason a synopsis of the method of implementation and the advantages and disadvantages of each of the seven changes is presented below. Table 42 summarizes the factors which affect the implementation of the changes. Included in the table are the requirements for implementation, advantages other than emissions, and constraints other than time and cost.

Increase Idle RPM

If all engines were to be operated on the ground at an increased idle RPM, fuel consumption would obviously increase. The increased operating cost shown in Table 41 is predicated on this assumption. The extent to which the idle RPM can increase is constrained by the capacity of the aircraft brakes-- in particular, by the need to avoid overheating and excessive wear of the brakes. Implementation of an increase in idle RPM requires only a modification of cockpit procedure since the idle speed is fully under the pilot's control. Thus no prominent initial costs would occur with implementation.

This control method would probably not be adopted without a corresponding reduction in the number of engines operating, so that total aircraft thrust would remain essentially the same. Brake problems would in this way be eliminated. The net effect on the operating cost of this combination of control methods, as discussed below, could be a substantial reduction in fuel expenditures for ground operations. American Airlines, for example, cuts Boeing 727 fuel costs on the ground by shutting down the center engine and by operating the out-board engines at higher output levels.

Reduce Number of Engines During Taxi and Increase Idle RPM

Total aircraft thrust during ground operations can be maintained by using fewer engines operating at higher power output levels. Aircraft emissions would be reduced on two counts: shut-down engines would produce no emissions, and engines operating at higher output would produce less carbon monoxide and hydrocarbon emissions. The change in airport procedure would call for unnecessary engines to be shut down upon landing and not to be restarted until at the end of the runway prior to departure. Whether one or two engines would be necessary for effective ground operations to be maintained at airports remains an open question. However, except for an answer to this question, implementation of the change would not be difficult since no equipment purchase or construction is entailed. Indeed, the suggested change in effect provides a more efficient method for achieving ground thrust requirements. Thus reduced fuel consumption would be a direct consequence.

The principal constraint on the minimal number of engines needed is the thrust required to resume taxi once the aircraft comes to a complete stop. A fully loaded Boeing 727 requires approximately 50 per cent of take-off power from two engines to resume taxi following a prolonged stop on a slight grade. Single engine operation would require a 100 per cent power level. The resulting jet blast along taxiways may prove hazardous. More space (e.g., in excess of 400 feet) between aircraft waiting for departure at the end of the runway would doubtlessly be needed with single engine operation. There is also a question on the safe maneuverability of two and four engine aircraft taxiing with unbalanced thrust produced by a single engine. Still, two engine ground operation appears reasonable with most commercial aircraft, and single engine operation is not out of the question. An airport procedure change to provide fire protection equipment and personnel would be necessary were engines to be started not at the gate, but at the end of the runway. A slightly more elaborate staging area at the end of the runway might also be needed at some airports.

The initial costs in implementing this ground operation change would be negligible. Reduced fuel consumption during ground operations would yield operating cost savings, as indicated by the negative numbers in Table 41. In particular, single engine operation would result in a $7.5 million annual cost savings at Los Angeles International Airport, and two engine operation would result in a $3 million savings. The additional labor cost for fire protection at the end of the runway is negligible by comparison-- less than one-half million dollars annually at LAX. Implementation of two engine operation should require little time since all factors other than fire protection are at the pilot's command. Single engine operation should await a series of tests to establish its practicality and safety. Since fuel costs as well as emission levels show decided gains from using fewer engines, a more detailed examination of this change is surely merited.

Controlled Gate Departure

The idea is to restrict engine operation on the ground to that required for taxi. The engines would be shut down at the gate. They would be started under a ground traffic control system which, among other things, would eliminate delays at the end of the runway. Such an airport traffic control system offers many evident advantages, but several factors militate against it.

The fundamental problem centers on the incompatibility of the times required for arrival and departure procedures if the latter are initiated from the gate rather than from the end of the runway. The time required for an aircraft to proceed from a final holding pattern to landing is of the order of magnitude of hundreds of seconds. The time required for an aircraft to be towed clear of the gate, to start engines, to taxi to the end of the runway, and to take-off is more of the order of magnitude of thousands of seconds. For example, the average taxi time alone at LA International Airport is 12 minutes (Ref 6). Moreover, the time from engine start to take-off is not uniform since it depends on the distance from the gate in question to the runway in use. For a controlled gate departure procedure to work with current peak load conditions, a complicated computer based system with automated communication techniques would be needed. The computer would be programmed on the basis of queuing theory to supply aircraft at the runway end automatically. The program would take into account the time required for the aircraft to reach the runway from its gate as well as the sequence in which permission to start is requested. Contingencies associated with arrivals, with weather, and with emergencies would be taken into consideration. Procedures for assuring fair treatment of all airlines regardless of terminal location and procedures for continuous monitoring after permission to start could in principle be introduced. Implementation of so complicated a ground control system would scarcely be straightforward, particularly given the current complexity of airport procedures with minimal ground control.

A second constraint on controlled gate departure is that much of the current delay at the end of runways results from an insufficient number of gates. Airlines dispatch aircraft to open a gate for use even though the aircraft will be unable to take off. Thus, a second requirement for controlled gate departure is either an increase in the number of gates or a parking area from which the ground traffic control system would take over.

For example, aircraft could be towed to the parking area under direction of the computer when gate space is needed, but when engine start permission can not yet be granted. Provision for 20 per cent of the gate capacity for such intermediate parking should suffice except during extraordinary circumstances.

A final constraint on controlled gate departure is the need to supply electrical power and air conditioning without the use of the aircraft engines. Boeing 707's, 720's, and McDonnell-Douglas DC-8's do not have on-board auxiliary power units, so that ground-based facilities would be required for these planes.

Introduction of an automated ground control system, as indicated in Table 41, involves substantial effort and expenditures. Were this ground operation change viewed purely in terms of reduced aircraft emissions, it would be of dubious merit. However, the orderly growth of commercial air transport in the present social climate is likely to require more effective utilization of existing airports. Automated ground control would surely provide one step toward improved utilization, though the step may seem small compared to improved air traffic control. Thus in judging the costs for controlled gate departure, shown in Table 41, the reader is encouraged to keep the total airport picture in mind.

Intermediate Passenger Transportation

From the point of view of emissions the use of lounges for transporting passengers to and from the aircraft is attractive only if the aircraft can be parked near the runway to be used. Otherwise taxi times would not be markedly reduced from those of current operation. Parking space for 75 aircraft near the runways at LA International is not remotely available. Safety questions may also discourage locating parking areas near runways. The large costs associated with modifying an existing airport to this type of operation result to a dominant extent from the cost of a parking area. In the case of a new airport this type of operation would appear far more practical since terminal construction costs can be reduced in far greater proportion than the cost of the lounges and parking space.

To implement this change at an existing airport requires purchase of land, construction of parking space near runways, purchase of passenger transportation vehicles, and possibly some added purchase of aircraft service and power supply vehicles. Again either ground-based or on-board auxiliary power units will have to suffice for air conditioning. Obviously airline schedules would also require revision. It might be competitive on a cost basis simply to build a new airport using this type of operation. Nevertheless, from the point of view of emission control the feasibility of this operation change is contingent upon whether aircraft parking areas can be made available quite close to runways. Since taxi time corresponding to runway length will at a minimum remain necessary, the gain in emissions will probably not be significant. The operating cost reduction indicated in Table 41 is predicated on a 50 per cent reduction in taxi and idle time. A more realistic assumption might be no reduction in taxi and idle time, in which case the operating cost at LAX would increase by $5 million per year.

Towing of Aircraft

The principal difficulty in towing aircraft between the runway and the terminal is the substantial time the operation would require. Tow vehicles are currently limited to 8 miles per hour loaded (15 miles per hour unloaded); this speed drops off markedly on a grade (Ref 32). Thus the average time required from the gate until departure at LA International Airport will increase from 14 minutes to at least 30 minutes. The average time required for towing into the gate after landing will be around 20 minutes, as compared to a current taxi average of less than 7 minutes. Such increases in ground time would necessitate revision of airline schedules, particularly those associated with short-haul and shuttle type flights. Thus the implementation cost of a towing operation is a minor consideration compared to potential ramifications of the time loss problem. Several man-years of scheduling effort will be required per airport. Some new aircraft may be needed to maintain current capacity. There is even the possibility of lost revenue because, for example, the gate-to-gate time from Los Angeles to San Francisco will double.

In assessing the cost of towing aircraft, several assumptions were made. First, it was assumed that with proper scheduling the increased ground time could be absorbed in such a way as to avoid loss of revenue to the airlines. Such scheduling would require larger than normal implementation labor. A major operating expense would result from increased crew-hours during towing. It was assumed that for 400,000 operations at Los Angeles Airport the crew time would increase by 150,000 hours, at a cost of $200 per crew hour. When this expense is added to the cost of operating the tow vehicles, all cost savings associated with aircraft engine fuel consumption are offset.

Implementation of the towing procedure thus requires not only additional towing vehicles, but also schedule modifications to allow for more than a 100 per cent increase in ground taxi times. The alternative of new tow vehicle designs capable of 30 mile per hour operation is possible, but it would require the development of a new generation of tow equipment and the formulation of quite different ground rules for towing safety and reliability. Towing would finally require the on-board auxiliary power units to supply adequate air conditioning throughout the towing period; special provisions would be needed for those aircraft without on-board auxiliary power units.

Ground-Based Auxiliary Power Supply

There are two ways in which on-board auxiliary power units could be eliminated from use while at the gate: by using portable electric and air supplies or by equipping each gate with a centrally supplied air and electric system. The latter method is of limited practicality except possibly for a newly designed airport. With existing airports mobile units are more feasible. Implementation will require purchase of adequate equipment. From the point of view of over-all ground operation, ignoring emissions, experience with the first generation of jet powered aircraft has led to the standard use of on-board auxiliary power units. The operational complexities associated with ground-based equipment are well known (Ref 33).

Auxiliary Equipment to Empty Fuel Drainage Reservoirs

Equipment has recently been developed for extracting and temporarily storing the fuel which collects in the engine fuel drainage reservoirs (Ref 34). The device hooks up to each engine in turn, and it would be used as part of the standard aircraft servicing procedure at the terminal gate. The devices cost $500 per unit. One per gate should suffice. Thus at Los Angeles International Airport only a $38,000 expenditure is needed to eliminate fuel dumping from the take-off procedure. The equipment in question is currently being demonstrated. Implementation could proceed quite rapidly once equipment is purchased and personnel are trained.

EMISSIONS MEASUREMENT

Introduction

Reliable methods of measuring pollutant emission rates from aircraft engines are required to support a program of emission control. Emission measurements are required to evaluate the effectiveness of control methods, and specific measurement methods must be incorporated in emission control standards.

An assessment has been conducted of the state of emission measurement technology to determine whether measurement techniques are sufficiently well-advanced to support the development of emission control methods and the implementation of emission standards for aircraft engines. The conclusion drawn from this assessment is that current measurement technology will meet most of the requirements of an emission control program. Certain measurement techniques are inadequate at present but development of improved techniques appears to be proceeding at a satisfactory rate.

Measurement of emission rates from an aircraft engine involves three major requirements:

1. A test procedure specifying engine operating conditions.
2. A sampling technique for obtaining a representative sample of exhaust gas.
3. Analysis instrumentation for determining pollutant concentrations in the exhaust gas sample.

Aircraft engine manufacturers and certain government agencies have devoted substantial effort toward providing for these requirements for emissions measurements for turbine engines. Representatives of these organization have formed a committee under the auspices of the Society of Automotive Engineers, referred to as the SAE E-31 Committee, for the purpose of defining standard measurement procedures and equipment. This assessment of turbine engine emissions measurement technology is based to large degree on the work of the SAE E-31 Committee.

Less progress has been made in defining measurement technique specifically applicable to aircraft piston engines. The techniques which have been developed for automobile engines are applicable in general to aircraft engines.

Test Procedures

Two types of test procedures can be used in measuring emissions from mobile sources. In the first type, emission rates of all pollutants of interest are measured at each steady state engine operating condition. These measured rates are then averaged, with appropriate weighting factors, to determine the total emissions for a complete operating cycle. In the second type of procedure, the engine is actually operated through a complete operational cycle and a composite sample is collected and analyzed. The weighted average emission rate for the operational cycle is obtained directly. This procedure is more effective for operating cycles which involve transient operations such as starting and acceleration.

Only the first type of procedure has been used to date with aircraft engines. Operational cycles which have been defined for aircraft generally include steady operating conditions only. An additional factor is that current sampling techniques for turbine engines require long sampling times to assure that representative samples are obtained. With this requirement, it is not feasible to obtain composite samples for a complete operating cycle.

Test procedures for standardized emission measurements should be based on a sequence of measurements at well-defined, steady operating conditions. Conditions which affect emission rates should be defined carefully. These include engine speed and power level, fuel type, inlet air temperature, pressure, and humidity.

Exhaust Sampling Techniques

Turbine Engines

The primary objective in exhaust gas sampling is obtaining a representative sample of exhaust gas of a known quantity or at a known flow rate. Apparatus used for sampling generally consists of a probe, sampling line, a flow measuring device, a pump capable of drawing the desired flow rate through the system, and collection devices for capturing pollutant samples.

Effort is underway to standardize the design of sampling probes (Ref 35). The SAE E-31 Committee recommends that probes be of stainless steel with an orifice area such that the principle pressure drop occurs in the orifice itself. If a mixing probe is to be used, they specify that all sampling holes be equidiameter (Ref 36). The probe need not be designed to achieve isokinetic sampling since departures from this condition only cause errors for particulates whose diameters are greater than 3-5 microns. Particulate emissions from aircraft engines are primarily less than 1 micron in diameter. As a notable example of this lack of need for isokinetic sampling, Pratt & Whitney (Ref 37) tested an aircraft engine exhaust with two probes installed back to back: one facing upstream; the other downstream. No detectable difference in the smoke density was observed as measured by the two probes as a function of engine power level. Further, probe orientation was not critical as long as they were stationed within the exhaust stream and secondary air had not diffused into the stream.

The SAE E-31 Committee and others (Refs 38 and 39) have found that multipoint sampling of engine exhausts is necessary (due to wide spatial variations in stream characteristics) in order to achieve representative values of engine emission rates. The SAE therefore recommends that samples be collected at at least twelve locations at a minimum of three different radial positions in each of four sampling quadrants. The location of these twelve points is specified by the E-31 Committee; procedures are also identified for point location if more than twelve samples are collected. Either mixing or individual probes are acceptable (Ref 36). The SAE also recommends that the axial sampling plane be no further than one exit nozzle diameter from the engine exhaust. However, with afterburning engines, combustion is by no means complete at the engine exit plane. Champagne (Ref 40) reports that the Arnold Engineering Development Center is conducting tests to produce preliminary solutions to this problem; The E-31 Committee will attempt to write a separate standard for measurement of emissions from afterburning engines later this year.

The sampling line, which conveys the gas sample from the probe to the collection and measurement apparatus, must be designed such that no changes in sample composition or physical state occur during transit. The line must therefore be short, of small bore (0.18 to 0.32 in I. D., Ref 36), and be constructed of materials (stainless steel or Teflon) which do not adsorb or react chemically with pollutant materials (Ref 41). The line must also allow free passage of particulate matter. As an illustration of the necessity for these requirements, Reference 42 contains a discussion of the reduction of NO_x by CO when catalyzed by certain metals frequently used in sample lines. In sampling engine exhaust gases, it is also necessary to maintain the sampling line temperature at a level at which condensation of organic vapors and water do not occur (about 350 deg F, Ref 36). This requirement is more severe with turbine engines than with gasoline-fueled piston engines. Turbine engine fuels, which have higher boiling points than gasoline, give rise to organic emissions which also have high boiling points. This requirement for heating the sampling line often is neglected; however, the E-31 Committee has recommended in their test procedure that sample lines be heated to 350 deg F to minimize this adsorption/desorption phenomenon. At the present time, line heating is accomplished primarily via electrical heating tapes; however, their use has been somewhat problematic and heat transfer fluids may be employed in the future (Ref 43).

The types of pollutant collection devices to be used in a sampling system depend upon the measuring techniques to be employed. Many measuring techniques do not require pollutant collection, but indicate pollutant concentration directly by measuring some property of the gas sample. These techniques are utilized either by connecting the measuring device directly to the sampling system, or by collecting a gas sample in a container (grab sample) and transporting it to the measuring device. Separate (heated) sample lines may eventually be employed for grab samples to prevent their upsetting the flow into continuous monitoring equipment (Ref 44).

Piston Engines

Sampling techniques for aircraft piston engines are not as critical as with turbine engines since exhaust gases are thoroughly mixed when they reach the exhaust stack exit. Also, fewer condensible vapors are encountered and particulates generally are not measured. The sampling technique initially proposed by the Department of Health, Education, and Welfare for automobile emission measurements (Ref 45) appear to be appropriate for aircraft piston engines.

Instrumentation

Range and Accuracy Requirements

An analysis has been conducted of the range and accuracy of the instrumentation necessary to measure emission rates of all pollutants of concern from aircraft engines. Allowance has been made for potential reductions in emission rates resulting from future equipment modifications.

Pollutants Considered

In a previous characterization of aircraft engine exhaust gases (Ref 1), Northern Research and Engineering Corporation indicated that emissions that should be considered for control and measurement should include, but not be limited to: total organics (hydrocarbons), carbon monoxide, oxides of nitrogen, sulfur dioxide, carbon dioxide, total particulates, visible smoke, and odor. Reexamination of the literature (Refs 46 and 47) shows that species such as peroxyacyl nitrates, olefins, and aromatics (ingredients in photochemical smog); polynuclear hydrocarbons (potentially carcinagenic); acrolein (aldehyde) formaldehyde, carbonyls, and unsaturated hydrocarbons (all apparently related to odor intensity); ozone (oxidant); lead; and unburned fuel (including drainage) are now often cited as atmospheric contaminants emitted in aircraft engine exhausts. The majority of these species are, however, emitted in extremely low quantities and at concentrations below which satisfactory continuous measurement techniques have been developed. Furthermore, many of these species are constituents of emissions which are themselves difficult to measure. As a result, with the exception of total aldehydes and unburned fuel (including drainage), these additional species are omitted from this analysis.

Until recently, nitrogen oxides in aircraft engine exhausts were considered to consist primarily of NO with only trace quantities of other oxides. Recent measurements (Ref 34) with turbine engines have revealed, however, that NO_2 concentrations are not negligible under some conditions. Thus, two measurements for NO and NO_2, or a combined measurement for the two species, are required to indicate total NO_x emission rate.

Instrumentation Range

Existing data (Refs 1, 3, 37, 41, and 48 through 54) on aircraft engine exhaust emissions are summarized in Table 43. The column entitled "Recommended Range" in Table 44 gives the suggested sensitivity of instrumentation for each pollutant. These ranges reflect emissions levels of both piston and turbine aircraft now and in the near future after satisfactory control methods have been established. These ranges correspond in a large part to the forthcoming recommendations (Ref 36) of the Society of Automotive Engineers Committee E-31, which as produced an "Aerospace Recommended Practice" (Ref 55) covering the measurement of visible smoke from turbine engines under test cell conditions. The absence of data and specifications for smoke and odor emissions reflects the specialized nature of these emissions in that they are not measured and quantified in a conventional manner (Refs 55 and 56).

Instrument Accuracy

Automated pollution measurement instruments can, in general, measure specie concentration with an accuracy of ± 1 - 2 per cent (Ref 57). This sensitivity, however, does not reflect the circumstances under which the instruments are required to operate; that is, it does not reflect the entire "system" accuracy (Ref 58). Further, these limits are, in many cases, far more restrictive than practically necessary. The accuracies recommended in Table 44 therefore reflect the sensitivity which a given instrument should be required to meet, exclusive of interferences from other pollutant species, in characterizing aircraft engine exhausts. In a majority of cases, these recommendations are consistent with those proposed by the SAE E-31 Committee (Ref 36).

Instrument Availability

A wide variety of instruments are available for analyzing exhaust samples from aircraft engines. Broderick (Ref 59) compiled a table of measurement methods in use by nine organizations that are concerned with quantification of aircraft emissions. In this study, NREC contacted several additional organizations to expand and update this analysis. These organizations are:

1. Air Force Aero Propulsion Laboratory; Captain D. L. Champagne.
2. Cranfield Institute of Technology; by Dr. R. S. Fletcher of the NREC staff.
3. Rolls-Royce (Derby); Dr. Brian Edwards.
4. Lockheed-California Company; Mr. E. F. Versaw.
5. Southwest Research Institute; Mr. C. T. Hare.
6. AiResearch Manufacturing Company; Mr. J. M. Haasis.
7. U. S. Department of the Interior, Bureau of Mines; Mr. R. W. Hurn.
8. Curtiss-Wright Corporation; Mr. T. P. Gagandize.

Table 45 is a compilation of the results of Broderick's report and of this survey. In several cases, organizations use more than one method to determine a particular constituent; in several cases, organizations do not measure all of the pollutant species included in the table. The instruments listed in Table 45 and alternative instruments are described in the Appendix.

Recommendations

CO and CO_2

NREC concurs with the recommendations of the SAE E-31 Committee (Ref 36) and recommends the use of NDIR instrumentation for monitoring CO and CO_2. Low level emissions should be measured with supplemental instrumentation such as small gas chromatographs.

Total Hydrocarbons

NREC concurs with the recommendations of the SAE E-31 Committee (Ref 36) and recommends the use of FID instrumentation for monitoring total hydrocarbons. Low level emissions should be measured with supplemental instrumentation such as small gas chromatographs. Hydrocarbon distribution should be determined with gas chromatographs.

Oxides of Nitrogen (NO and NO_2)

NREC concurs partially with the recommendations of the SAE E-31 Committee and recommends the use of NDUV instrumentation for monitoring NO_2. However, chemiluminescence monitors are recommended for monitoring NO because of their greater accuracy at low NO concentrations.

SO_2

NREC recommends that SO_2 emissions be calculated from the sulfur content of the fuel rather than measured by any type of instrumentation. If a measurement program is selected, the West-Gaeke wet chemical procedure is recommended. "Faristors" are not recommended at this time, as they have not yet been field tested in an aircraft emissions program.

Aldehydes

NREC recommends that the 3-MBTH wet chemical procedure be employed for measurement of total aliphatic aldehydes. Formaldehyde should be determined by the chromotropic acid procedure and acrolein by the 4-hexylresorcinol method.

Particulates

No instrument can be recommended at present for measuring mass emission rates of either dry or total particulates. Filtration or impingement techniques are not sufficiently sensitive to measure particulate concentrations in current engines. Until suitable instruments are developed, approximate indications of dry particulate emission rates can be obtained from correlations with smoke measurements.

Smoke

Smoke should be measured according to the procedures (and forthcoming sampling modifications) recommended in the SAE ARP-1179 (Ref 55).

Odor

NREC makes no recommendations for odor measurement other than suggesting that dilution thresholds be determined for aircraft exhausts by means of human odor panels.

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TABLES

TABLE 1 - AIRCRAFT CLASSIFICATION SYSTEM

Aircraft					Representative Engine			Engines per Air-craft
Category	Class	Ref 1 Classi-fication	Type	Examples	Model	Type	Thrust or Power	
Air Carrier	1	-	Supersonic Transport	Concorde Tupolev TU-144	R-R/Snecma Olympus 593	Turbojet	37,290 LB-T	4
	2	-	Jumbo Jet Transport	Boeing 747 Douglas DC-10	P&WA JT9D	Turbofan	47,000 LB-T	4
	3	1	Long-Range Jet Transport	Boeing 707 Douglas DC-8	P&WA JT3D	Turbofan	18,000 LB-T	4
	4	2	Medium-Range Jet Transport	Boeing 727 Douglas DC-9	P&WA JT8D	Turbofan	14,500 LB-T	2.6
	5	4	Turboprop Transport	Lockheed Electra Fairchild Hiller FH-227	Allison 501-D13	Turbo-prop	3,750 ESHP*	2.5
General Aviation	6	3	Business Jet	Lockheed Jetstar North American Sabreliner	P&WA JT12	Turbojet	3,300 LB-T	2.1
	7	6	Piston-Engine Utility	Cessna 210 Centurion Piper 32-300 Cherokee Six	Continental 10-520-A	Opposed Piston	285 ESHP	1**
Military	8	-	Over 400,000 lbs Gross Weight	Boeing Stratofortress	P&WA TF33-P-3	Turbofan	17,000 LB-T	-
	9	-	100,000 lbs - 400,000 lbs Gross Weight	Lockheed Starlifter	P&WA TF33-P-7	Turbofan	21,000 LB-T	-

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* Shaft Power

** Representative of VanNuys and Tamiami

TABLE 1 - AIRCRAFT CLASSIFICATION SYSTEM (CONTINUED)

Aircraft					Representative Engine			Engine per Aircraft
Category	Class	Ref 1 Classification	Type	Examples	Model	Type	Thrust or Power	
Military	10	-	10,000 lbs - 100,000 lbs Gross Weight	LTV Crusader	P&WA J57-P-20	Turbojet	18,000 LB-T	-
	11	-	Under 10,000 lbs Gross Weight	Cessna 172	Continental 10-360	Opposed Piston	210 ESHP	-
V/STOL	12	7	Helicopters and V/STOL	Sikorsky S-61 Vertol 107	General Electric CT58	Turboshaft	1870 ESHP	2

TABLE 2 - TURBINE ENGINES IN THE U. S. AIR CARRIER FLEET
(JANUARY, 1970)

Aircraft Class	Manufacturer	Model	Type	Maximum Power or Thrust	Number in Use
5	AiResearch Division Garrett Corporation	TFE731-2K	Turbofan	3500 LB-T	—
		TPE331-2-201A	Turboprop	665-715 ESHP	4
		TPE331-43	Turboprop	575 ESHP	—
				Total	4
5	Allison Division General Motors Corporation	501-D13	Turboprop	3750 ESHP	536
		501-D22A	Turboprop	4680 ESHP	84
				Total	620
1	General Electric Company	GE4	Turbojet	68600 LB-T	—
2		CF6-6D	Turbofan	40000 LB-T	—
2		CF6-50A	Turbofan	49000 LB-T	—
4		CJ805-3B	Turbojet	11650 LB-T	164
3		CJ805-23B	Turbofan	16100 LB-T	24
4		CJ610-1,9,6	Turbojet	2850-3100 LB-T	8
4		CF700-2D2	Turbofan	4250 LB-T	10
				Total	206
2	Pratt & Whitney Aircraft Division United Aircraft Corporation	JT9D-3A,7,15	Turbofan	45000-47000 LB-T	64
3		JT3C-6,7	Turbojet	13500	160
3		JT3D-1,3B,7	Turbofan	17000-19000 LB-T	2811
3		JT4A-3,9,11	Turbojet	17500 LB-T	376
4		JT8D-1,9,7	Turbofan	14500 LB-T	2881
4		JT12A-8	Turbojet	3300 LB-T	8
				Total	6300
1	Rolls-Royce Ltd.	Olympus 593	Turbojet	37290 LB-T	—
2		RB.211-22B	Turbofan	42000 LB-T	—
3		Conway RCo.12MK508,509	Turbofan	17500 LB-T	—
3		Conway RCo.42,43MK540	Turbofan	20370 LB-T	—
3		Spey RSp4MK512	Turbofan	12550 LB-T	120
4		Avon RA-29-533	Turbojet	12600 LB-T	40
4		Spey RSp4MK511	Turbofan	11400 LB-T	—
4		Bristol-Viper 522	Turbojet	3360 LB-T	2

TABLE 2 - TURBINE ENGINES IN THE U. S AIR CARRIER FLEET (CONTINUED)
(JANUARY, 1970)

Aircraft Class	Manufacturer	Model	Type	Maximum Power or Thrust	Number in Use
5	Rolls-Royce Ltd.	Dart Da6-MK514	Turboprop	1850 ESHP	72
5		Dart Da7-MK532	Turboprop	2230 ESHP	148
5		Dart Da10-MK542	Turboprop	3025 ESHP	148
5		Dart Da7-MK529	Turboprop	2100 ESHP	-
5		Dart Da6-MK510	Turboprop	1670 ESHP	32
5		Tyne 12MK515	Turboprop	5500 ESHP	36
					Total 598
5	Societe Turbomeca	Astazou XII	Turboprop	731 ESHP	-
5		Bastan VIC	Turboprop	1065 ESHP	-
					Total 0
5	United Aircraft of Canada	PT6A-20,27	Turboprop	579-715 ESHP	26
					Total 26
TOTAL TURBINE ENGINES					7754

Sources: References 7, 8, 9, 10, and 11

TABLE 3A - TOTAL ENGINES IN THE U. S. GENERAL AVIATION FLEET
(TURBINE ENGINES) (JANUARY, 1970)

Aircraft Class	Manufacturer	Model	Type	Maximum Power or Thrust	Number in Use
6	AiResearch Division Garrett Corporation	TPE331-3U	Turboprop	840 ESHP	88
6		TPE331-1-151A	Turboprop	665-715 ESHP	186
6		TPE331-43	Turboprop	575 SHP	222
6		ATF-3	Turbofan	4050 LB-T	30
6		TFE-731-2K	Turbofan	3500 LB-T	22
					Total 548
6	Allison Division General Motors Corporation	501-D13	Turboprop	3750 ESHP	12
					Total 12
6	General Electric Company	CJ610-1,6,9	Turbojet	2850-3100 LB-T	652
6		CF700-2D2	Turbofan	4250 LB-T	200
					Total 852
6	Pratt & Whitney Aircraft Division United Aircraft Corporation	JT12A-8	Turbojet	3300 LB-T	642
6		JT8D-9,7	Turbofan	14500 LB-T	310
					Total 952
6	Rolls-Royce Ltd.	Dart Da7MK-529	Turboprop	2100 ESHP	562
6		Spey RSp4MK511-8	Turbofan	11400 LB-T	138
6		Viper 522	Turbojet	3360 LB-T	134
6		Viper 601	Turbojet	3750 LB-T	58
6		Dart Da7MK520	Turboprop	1815 ESHP	76
6		Dart Da10MK542-4	Turboprop	3025 ESHP	46
6		Tyne 12MK515	Turboprop	5500 ESHP	16
					Total 1030
6	Societe Turbomeca	Astazou XIV MK1	Turboprop	600 ESHP	26
					Total 26
6	United Aircraft of Canada	JT15D-1	Turbofan	2200 LB-T	2
6		PT6A-20,2,28	Turboprop	579-715 ESHP	1387
					Total 1389
TOTAL TURBINE ENGINES					4809

Sources: References 7, 8, 9, 10, and 11

TABLE 3B - TOTAL ENGINES IN THE U. S. GENERAL AVIATION FLEET (PISTON ENGINES) (JANUARY, 1970)

Aircraft Class	Manufacturer	Model	Type	Maximum Power at Sea Level	Number in Use
7	Avco Lycoming Division Avco Corporation	0-235	Normal Carburation	115 ESHP	318
		0-290	Normal Carburation	140 ESHP	1302
		0-320	Normal Carburation	160 ESHP	20400
		0-360	Normal Carburation	180 ESHP	7610
		0-540	Normal Carburation	260 ESHP	16200
		GO-480	Normal Carburation and Gear	295 ESHP	217
		10-320	Fuel Injection	160 ESHP	3010
		10-360	Fuel Injection	200 ESHP	458
		10-540	Fuel Injection	300 ESHP	2430
		TIO-320	Turbocharged Fuel Injected	—	87
		TIO-360	Turbocharged Fuel Injected	200 ESHP	12
		TIO-540	Turbocharged Fuel Injected	310 ESHP	2790
		TIO-541	Turbocharged Fuel Injected	380	1150
		TIO-547	Turbocharged Fuel Injected	—	258
		IGSO-480	Fuel Injected, Geared, Supercharged	340 ESHP	1040
		IGSO-540	Fuel Injected, Geared, Supercharged	380 ESHP	53
					Total 57335
7	Continental Motors Division Teledyne Corporation	0-200	Normal Carburation	100 ESHP	30600
		0-300	Normal Carburation	145 ESHP	2180
		0-470	Normal Carburation	240 ESHP	17050
		GO-300	Normal Carburation and Gear	—	1578
		W-670		—	129

TABLE 3B - TOTAL ENGINES IN THE U. S. GENERAL AVIATION FLEET (CONTINUED)
(PISTON ENGINES) (JANUARY, 1970)

Aircraft Class	Manufacturer	Model	Type	Maximum Power at Sea Level	Number in Use
	Continental Motors Division Teledyne Corporation	10-360	Fuel Injection	210 ESHP	429
		10-470	Fuel Injection	260 ESHP	4960
		10-520	Fuel Injection	300 ESHP	12930
		TSI-520	Turbocharged Fuel Injected	310 ESHP	3330
		GTS10-520	Fuel Injected, Geared, Supercharged	435	58
					Total 73244
7	Curtiss-Wright Corporation	R-975	Radial	475 ESHP	34
		R1820	Radial	1200 ESHP	350
		R2600	Radial	1700 ESHP	136
		R4360	Radial	2200 ESHP	299
					Total 819
7	Fairchild Engine Division Fairchild Aircraft Company	Ranger R6-440C		200 ESHP	55
					Total 55
7	Franklin Engine Company, Inc. Subsidiary of Allied Aero Industries	2A-120	Horizontal-Opposed	50-90 ESHP	26
		4A-235	Horizontal-Opposed	65-80 ESHP	8
		6A-335	Horizontal-Opposed	150-165 ESHP	242
		6A-350	Horizontal-Opposed	100-215 ESHP	1900
					Total 2176
7	Jacobs-Page Aircraft Engine Company	R-755A2	Radial	245 ESHP	394
		R-755B2	Radial	300 ESHP	275
					Total 669
7	Pratt & Whitney Aircraft Division United Aircraft Corporation	R-985	Radial	450 ESHP	92
		R-1340	Radial	600 ESHP	1190
		R-1830	Radial	1050 ESHP	904
		R-2000	Radial	1450 ESHP	78
		R-2800	Radial	2300 ESHP	554
					Total 2818
	TOTAL PISTON ENGINES				137116

Sources: References 7, 8, 9, and 11

TABLE 4 - TOTAL ENGINES IN THE U. S. MILITARY FLEET*
(TURBINE AND PISTON ENGINES) (JANUARY, 1970)

Aircraft Class	Manufacturer	Model	Type	Maximum Power or Thrust	Number in Use
8	General Electric Company	TF39	Turbofan	41100 LB-T	258
	Pratt & Whitney Aircraft Division United Aircraft Corporation	J57	Turbojet	18000 LB-T	2000
					Total 2258
9	Allison Division General Motors Corporation	T56	Turboprop	4910 ESHP	1769
	Curtiss-Wright Corporation	R-3350	Radial Turbo-Comp.	3400 ESHP	200
	Pratt & Whitney Aircraft Division United Aircraft Corporation	JT3D	Turbofan	18000 LB-T	28
		TF33	Turbofan	21000 LB-T	2400
		T34	Turboprop	6000 ESHP	215
					Total 4612
10	AiResearch Division Garrett Corporation	T76	Turboprop	715 ESHP	826
	Allison Division General Motors Corporation	T41	Turbofan	15000 LB-T	—
		T56	Turboprop	4910 ESHP	4000
		T63	Turboprop	317 ESHP	1906
		J71	Turbojet	—	135
	Avco Lycoming Division Avco Corporation	T53	Turboprop	1900 ESHP	12449
		YT55	Turboprop	3750 ESHP	2493
	Curtiss-Wright Corporation	J65	Turbojet	10500 LB-T	137
		R1300	Radial	600 ESHP	11
		R1820	Radial	1200 ESHP	2069
		R3350	Radial	3400 ESHP	217

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* Including Military Helicopters

TABLE 4 - TOTAL ENGINES IN THE U. S. MILITARY FLEET* (CONTINUED) (TURBINE AND PISTON ENGINES) (JANUARY, 1970)

Aircraft Class	Manufacturer	Model	Type	Maximum Power or Thrust	Number in Use
	General Electric Company	T58	Turboshaft	1870 ESHP	3159
		T64	Turboshaft	3925 ESHP	458
		J79	Turbojet	17900 LB-T	10083
		J85	Turbojet	2900-5000 LB-T	4000
	Pratt & Whitney Aircraft Division United Aircraft Corporation	TF30	Turbofan	13400 LB-T	1509
		TF33	Turbofan	21000 LB-T	1307
		J52	Turbojet	11200 LB-T	3733
		J57	Turbojet	16900 LB-T	6231
		J58	Turbojet	30000 LB-T	—
		J60	Turbojet	3300 LB-T	878
		T73	Turboshaft	4500 ESHP	208
		J75	Turbojet	26500 LB-T	1422
		F100	Turbofan	30000 LB-T	—
		R1340	Radial	600 ESHP	22
		R2800	Radial	2300 ESHP	70
	Rolls-Royce Ltd.	Dart MK 529-8X	Turboprop	2100 ESHP	—
					Total 57323
11	Allison Division General Motors Corporation	J33	Turbojet	4600 LB-T	20
	Avco Lycoming Division Avco Corporation	O-435	Normal Carburation	260 ESHP	814
		GO-480	Normal Carburation	295 ESHP	419
	Continental Motors Division Teledyne Corporation	J69	Turbojet	1420 LB-T	5554
		O-470	Normal Carburation	240 LB-T	173
	General Electric Company	J85	Turbojet	2900-5000 LB-T	3020
	United Aircraft of Canada	T74 (PT6)	Turboshaft	579 ESHP	432
					Total 10432
TOTAL MILITARY ENGINES					74625

Sources: References 1, 7, 8, 9, and 11

TABLE 5A - TOTAL ENGINES IN THE U. S. CIVIL HELICOPTER AND V/STOL FLEET (TURBINE AND PISTON ENGINES) (JANUARY, 1970)

Aircraft Class	Manufacturer	Model	Type	Maximum Power or Thrust	Number in Use
12*	Allison Division General Motors Corporation	250-C18	Turboshaft	317 ESHP	836
	Avco Lycoming Division Avco Corporation	T53	Turboshaft	1900 ESHP	323
		VO-435	Vertical-Opposed, Normal Carburation	265 ESHP	550
		VO-540	Vertical-Opposed, Normal Carburation	305 ESHP	755
		HIO-360	Horizontal-Opposed, Fuel Injected	205 ESHP	530
		IVO-360	Vertical-Opposed, Fuel Injected	180 ESHP	100
	General Electric Company	T58	Turboshaft	1870 ESHP	281
		CT58	Turboshaft	1870 ESHP	29
TOTAL CIVIL HELICOPTER ENGINES					3404

Sources: References 7, 8, 9, and 11

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* Helicopters

TABLE 5B - TOTAL ENGINES IN THE U. S. CIVIL HELICOPTER AND V/STOL FLEET (TURBINE AND PISTON ENGINES) (JANUARY, 1970)

Aircraft Class	Manufacturer	Model	Type	Maximum Power or Thrust	Number in Use
12*	AiResearch Division Garrett Corporation	TPE331	Turboshaft	715 ESHP	15
	Avco Lycoming Division Avco Corporation	GO-480	Geared, Normal Carburation	295 ESHP	46
		O-540	Normal Carburation	300 ESHP	24
		ALF301	Turbofan	2730 LB-T	—
	General Electric Company	J85	Turbojet	2900-5000 LB-T	2
		YT58	Turboshaft	1870 ESHP	4
		CF700	Turbojet	4250 LB-T	1
	Pratt & Whitney Aircraft Division United Aircraft Corporation	R2000	Radial	1450 ESHP	14
	United Aircraft of Canada	PT6A	Turboshaft	715 ESHP	285
TOTAL V/STOL ENGINES					391
TOTAL CLASS 12 ENGINES					3795

Sources: References 7, 8, 9, and 11

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* V/STOL

TABLE 6

ENGINE CLASSIFICATION

T1 - Small turbine engines (nominally less than 6000 LB-T or equivalent shaft horsepower).

Examples: JT12A, T58

T2 - Turbine engines (nominally 6000 to 29,000 LB-T or ESHP).

Examples: JT8D, CJ805

T3 - Turbine engines (nominally 29,000 to LB-T or ESHP and greater)

Examples: JT9D, CF6

P1 - Piston engines (all opposed configuration engines).

TABLE 7

AIRCRAFT TURBINE ENGINE CLASSIFICATION SYSTEM

Engine Class	Manufacturer	Engine Family Model No.	Engine Type	Thrust or Power	Type Combustor	No. in Use A	No. in Use G	No. in Use M	No. in Use T	Maximum Production Capacity Per Year	Aircraft Classes	Total No. In Use
TI-1	Allison Div.	J33	TJ	4600 LB-T	--	-	-	20	20	20	11	
TI-2	GMC	J71	TJ	--	--	-	-	135	135	100	10	
TI-3		T56	TP	4910 ESHP	CN (6)	-	-	5769	5769	1000	9,10	
TI-4		501	TP	3750 ESHP	CN (6)	620	12	-	632	500	5,6	
TI-5		T63	TP	317 ESHP	CA (1)	-	-	1906	1906	1000	10	
TI-6		250	TP	317 ESHP	CA (1)	-	836	-	836	500	12	9298
TI-7	AiResearch Div.	T76	TP	715 ESHP	A	-	-	826	826	--	10	
TI-8	Garrett Corp.	TPE331	TP	715 ESHP	A	4	511	-	515	--	12,5,6	
TI-9		ATF3	TF	4050 LB-T	A	-	30	-	30	--	6	
TI-10		TFE731	TF	3500 LB-T	A	-	22	-	22	--	5,6	1393
TI-11	Avco-Lycoming Div.*	T53	TS	1900 ESHP	A	-	323	12449	12772	1300	10,12	
TI-12	Avco Corp.	T55	TS	3750 ESHP	A	-	-	2493	2493	1000	10	
TI-13		ALF301	TF	2730 LB-T	A	-	-	-	-	650	--	15265
TI-14	Continental Motors	J69	TJ	1920 LB-T	A	-	-	5554	5554	600	11	5554
TI-15	General Electric Co.	T58	TS	1870 ESHP	CA (1)	-	285	3159	3444	600	10,12	
TI-16		CT58	TS	1870 ESHP	CA (1)	-	29	-	29	300	12	
TI-17		GE1	TJ	5000 LB-T	CA (1)	-	-	-	-	--	--	
TI-18		GE12	TS	1500 ESHP	A	-	-	-	-	--	--	
TI-19		T64	TS	3925 ESHP	A	-	-	458	458	150	10	
TI-20		J85	TJ	5000 LB-T	A	-	-	7022	7022	1000	10,11,12	
TI-21		CJ610	TJ	3100 LB-T	A	8	652	-	660	500	4,6	
TI-22		CF700	TF	4250 LB-T	A	10	201	-	211	500	4,6,12	11824

A = Air Carrier Fleet
G = General Aviation Fleet
M = Military Fleet
T = Total Engines in Use

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* Baseline Engine

TABLE 7 (CONTINUED)

AIRCRAFT TURBINE ENGINE CLASSIFICATION SYSTEM

Engine Class	Manufacturer	Engine Family Model No.	Engine Type	Thrust or Power	Type Combustor	No. in Use				Maximum Production Capacity Per Year	Aircraft Classes	Total No. In Use
						A	G	M	T			
TI-23	Pratt & Whitney Div.	J60	TJ	3300 LB-T	CN (8)	-	-	878	878	220	10	
TI-24	Vac.	JT12A	TJ	3300 LB-T	CN (8)	8	642	-	650	110	4,6,10	
TI-25		T73	TJ	4050 ESHP	CN (8)	-	-	208	208	200	10	
TI-26		T34	TP	6000 ESHP	CN (8)	-	-	215	215	60	9	
TI-27		PT2	TP	6000 ESHP	CN (8)	-	-	*	-	30	9	
TI-28		ST9	TS	1500 ESHP	--	-	-	*	-	--	--	
												1951
TI-29	Rolls-Royce Ltd.	Dart Mk 510	TP	1670 ESHP	CN (7)	32	-	-	32	--	5	
TI-30		514	TP	1850 ESHP	CN (7)	72	-	-	72	--	5	
TI-31		520	TP	1815 ESHP	CN (7)	-	76	-	76	--	6	
TI-32		529	TP	2100 ESHP	CN (7)	-	562	-	562	--	5.6	
TI-33		532	TP	2232 ESHP	CN (7)	148	-	-	148	--	5	
TI-34		542	TP	3025 ESHP	CN (7)	148	46	-	194	--	5,6	
TI-35		Tyne 12	TP	5500 ESHP	CN (10)	36	16	-	52	--	5,6	
												1136
TI-36	Bristol Eng. Div.	VIPER 522	TJ	3360 LB-T	CA (1)	2	134	-	136	--	4,6	
TI-37	Rolls-Royce Ltd.	601	TJ	3750 LB-T	CA (1)	-	58	-	58	--	6	
												194
TI-38	Societe Turbomeca	ASTAZOU XIV	TP	600 ESHP	A	-	26	-	26	--	6	
												26
TI-39	United Aircraft	JT15	TF	2200 LB-T	A	-	2	-	2	--	6	
TI-40	of Canada Ltd.	T74	TS	715 ESHP	A	-	-	432	432	100	5	
TI-41		PT6	TS	715 ESHP	A	26	1672	-	1698	50	5,11,12	
												2132
TI-42	Westinghouse	J34	TJ	3400 LB-T	--	-	-	*	-	--	10	

		TOTAL TI ENGINES										48773

* Population unknown.

A = Air Carrier Fleet
G = General Aviation Fleet
M = Military Fleet
T = Total Engines in Use

TABLE 7 (CONTINUED)

AIRCRAFT TURBINE ENGINE CLASSIFICATION SYSTEM

Engine Class	Manufacturer	Engine Family Model No.	Engine Type	Thrust or Power	Type Combustor	No. in Use A	No. in Use G	No. in Use M	No. in Use T	Maximum Production Capacity Per Year	Aircraft Classes	Total No. In Use
T2-1	Allison Div. GMC	T41	TF	15000 LB-T	CN (10)	-	-	-	-	500	10	----
T2-2	Curtiss-Wright Corp	J65	TJ	10500 LB-T	CA (1)	-	-	137	137	100	10	137
T2-3	General Electric Co.	J79	TJ	17900 LB-T	CN (10)	-	-	10083	10083	1400	10	
T2-4		CJ805	TJ,TF	11650,16100	CN (10)	188	-	-	188	700	3,4	
T2-5		TF34	TF	9000 LB-T	A	-	-	-	-	--	--	10271
T2-6	Pratt & Whitney Div. Vac.*	J52	TJ	11200 LB-T	CN (9)	-	-	3733	3733	500	10	
T2-7		JT8D	TF	14500 LB-T	CN (9)	2831	310	-	3191	250	4,6	
T2-8		J57	TJ	18000 LB-T	CN (8)	-	-	8231	8231	2000	8,10	
T2-9		JT3C	TJ	13500 LB-T	CN (8)	160	-	-	160	1000	3	
T2-10		J75	TJ	26500 LB-T	CN (8)	-	-	1422	1422	300	10	
T2-11		JT4A	TJ	17500 LB-T	CN (8)	376	-	-	376	150	3	
T2-12		TF33	TF	21000 LB-T	CN (8)	-	-	3707	3707	700	9,10	
T2-13		JT3D	TF	19000 LB-T	CN (8)	2811	-	28	2839	350	3,9	
T2-14		TF30	TF	13400 LB-T	CN (8)	-	-	1509	1509	400	10	
T2-15		JTF10	TF	13400 LB-T	CN (8)	-	-	-	-	200	--	25168
T2-16	Rolls-Royce Ltd.	AVON RA29	TJ	12600 LB-T	CN (8)	40	-	-	40	--	4	
T2-17		CONWAY C012	TF	17500 LB-T	CN (10)	-	-	-	-	--	3	
T2-18		CONWAY C042	TF	20370 LB-T	CN (10)	-	-	-	-	--	3	
T2-19		SPEY MK 511	TF	11400 LB-T	CN (10)	-	138	-	138	--	4,6	
T2-20		MK 512	TF	12550 LB-T	CN (10)	120	-	-	120	--	4	298
				TOTAL T2 ENGINES								35874

A = Air Carrier Fleet
G = General Aviation Fleet
M = Military Fleet
T = Total Engines in Use

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* Baseline Engine

TABLE 7 (CONTINUED)

AIRCRAFT TURBINE ENGINE CLASSIFICATION SYSTEM

Engine Class	Manufacturer	Engine Family Model No.	Engine Type	Thrust or Power	Type Combustor	No. in Use				Maximum Production Capacity Per Year	Aircraft Classes	Total No. In Use
						A	G	M	T			
T3-1	General Electric* Co.	TF39	TF	41100 LB-T	A	-	-	258	258	500	8	258
T3-2		CF6	TF	40000 LB-T	A	-	-	-	-	250	2	
T3-3		GE9	TF	--	--	-	-	-	-	--	--	
T3-4		GE4	TJ	68600	A	-	-	-	-			
T3-5	Pratt & Whitney Div. Vac.	J58	TJ	30000 LB-T	--	-	-	-	-	500	10	64
T3-6		JT11D	TJ	30000 LB-T	--	-	-	-	-	250	--	
T3-7		JT9D	TF	47000 LB-T	A	64	-	-	64	500	2	
T3-8	Rolls-Royce Ltd.	RB211	TF	42000 LB-T	A	-	-	-	-	--	2	----
T3-9		OLYMPUS 593	TJ	37290 LB-T	A	-	-	-	-	--	1	
	TOTAL T3 ENGINES											322

A = Air Carrier Fleet
G = General Aviation Fleet
M = Military Fleet
T = Total Engines in Use

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* Baseline Engines

TABLE 8

AIRCRAFT PISTON ENGINE CLASSIFICATION SYSTEM*

Engine Class	Manufacturer	Engine Family Model No.	Engine Type	Thrust or Power	No. in Use G	No. in Use M	No. in Use T	Maximum Production Capacity per year	Aircraft Classes	Total in Use
PI-1	Avco-Lycoming	0-235	HO,NC	115 ESHP	318	-	318	1173	7	
PI-2	Avco Corporation	0-290	HO,NC	140	1302	-	1302	15	7	
PI-3		0-320	HO,NC	160	20400	-	20400	3700	7	
PI-4		0-360	HO,NC	180	7610	-	7610	2100	7	
PI-5		0-435	VO,NC	260	-	814	814	--	11	
PI-6		0-540	HO,NC	260	16224	-	16224	2700	7,12	
PI-7		GO-480	G,HO,NC	280	263	419	682	306	7,11,12	
PI-8		IO-320	I,HO	160	3010	-	3010	--	7	
PI-9		HIO-360	I,HO	180	530	-	530	--	12	
PI-10		IO-360	I,HO	200	458	-	458	--	7	
PI-11		IO-540	I,HO	300	2430	-	2430	--	7	
PI-12		TIO-320	T,I,HO	160	87	-	87	--	7	
PI-13		TIO-360	T,I,HO	200	12	-	12	--	7	
PI-14		TIO-540	T,I,HO	310	2790	-	2790	--	7	
PI-15		TIO-541	T,I,HO	380	1150	-	1150	200	7	
PI-16		TIO-547	T,I,HO	--	258	-	258	--	7	
PI-17		IGSO-480	I,G,S	340	1040	-	1040	--	7	
PI-18		IGSO-540	I,G,S	380	53	-	53	--	7	
PI-19		VO-435	VO,NC	260	550	-	550	--	12	
PI-20		VO-540	VO,NC	305	755	-	755	--	12	
PI-21		IVO-360	I,VO	180	100	-	100	--	12	60573
PI-22	Continental Motors	0-200	HO,NC	100	30600	-	30600	3187	7	
PI-23	DIV, Teledyne Corp.	0-300	NO,NC	145	2180	-	2180	1700	7	
PI-24		0-470	HO,NC	240	17050	173	17223	--	7,11	
PI-25		GO-300	G,HO,NC	145	1578	-	1578	--	7	
PI-26		W-670	--	--	129	-	129	--	7	
PI-27		IO-360	I,HO	210	429	-	429	554	7	
PI-28		IO-470	I,HO	260	4960	-	4960	2000	7	

G = General Aviation Fleet
M = Military Fleet
T = Total Piston Fleet

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* Radial engines not included

TABLE 8 (CONTINUED)

AIRCRAFT PISTON ENGINE CLASSIFICATION SYSTEM

Engine Class	Manufacturer	Engine Family Model No.	Engine Type	Thrust or Power	No. in Use G	No. in Use M	No. in Use T	Maximum Production Capacity per year	Aircraft Classes	Total in Use
PI-29		IO-520	I,HO	300	12930	-	12930	2600	7	
PI-30		TSIO-520	T,I,HO	310	3330	-	3330	--	7	
PI-31		GTSIO-520	G,T,I,HO	435	58	-	58	--	7	
										73417
PI-32	Franklin Engine CO	2A-120	HO,NC	50-90	26	-	26	--	7	
PI-33		4A-235	HO,NC	65-80	8	-	8	--	7	
PI-34		6A-335	HO,NC	200	242	-	242	--	7	
PI-35		6A-350	HO,NC	230	1900	-	1900	--	7	
										2176
	TOTAL PISTON ENGINES									143,130

HO = Horizontally Opposed
VO = Vertically Opposed
R = Radial
NC = Normal Carburetion
I = Fuel Injection
G Geared Propeller Drive
T = Turbo-Supercharged
S = Supercharged

G = General Aviation Fleet
M = Military Fleet
T = Total Piston Fleet

TABLE 9

AIRCRAFT TURBINE AND PISTON ENGINE CLASSIFICATION SUMMARY

Class	Total Families (Population)	Air Carrier Families (Population)	General Aviation Families (Population)	Total Civil Aviation Families (Population)	Total Military Families (Population)
T1	42 (48773)	6* (1114)	16* (6137)	22 (7251)	20 (41522)
T2	20 (35874)	10 (6576)	2 (448)	12 (7024)	8 (28850)
T3	9 (322)	7 (64)	0 (0)	7 (64)	2 (258)
TURBINE TOTAL POPULATION	84969	7754	6585	14339	70630

* Placement of engine families in these categories is based upon majority of engine applications since some families are used in both air carrier and general aviation categories.

Class	Total Families (Population)	Air Carrier Families (Population)	General Aviation Families (Population)	Total Civil Aviation Families (Population)	Total Military Families (Population)
** **PI	39 (136166)	(***) (***)	34 (134760)	34 (134760)	1* (1406)
PISTON TOTAL POPULATION	136166	---	134760	134760	1406

** Radial Engines not included

*** Air carrier piston engines not included

TABLE 10

EMISSION CONTROL METHODS: MODIFICATION OF TURBINE ENGINES

I. Methods applicable to existing engines

t1. Combustion chamber redesign (minor) - Minor modification of combustion chamber and fuel nozzle to achieve best state-of-art emission performance.

t2. Combustion chamber redesign (major) - Major modification of combustion chamber and fuel nozzle incorporating advanced fuel injection concepts (carburetion or prevaporization).

t3. Fuel drainage control - Modify fuel supply system or fuel drainage system to eliminate release of drained fuel to environment.

t4. Divided fuel supply system - Provide independent fuel supplies to subsets of fuel nozzles to allow shut-down of one or more subsets during low power operation.

t5. Water injection - Install water injection system for short duration use during maximum power (take-off and climb-out) operation.

t6. Modify compressor air bleed rate - Increase air bleed rate from compressor at low power operation to increase combustor fuel-air ratio.

II. Methods applicable to future engines

t7. Variable-geometry combustion chamber - Use of variable airflow distribution to provide independent control of combustion zone fuel-air ratio.

t8. Staged injection combustor - Use of advanced combustor design concept involving a series of combustion zones with independently-controlled fuel injection in each zone.

TABLE 11

EMISSION CONTROL METHODS: MODIFICATION OF PISTON ENGINES

I. Methods applicable to existing engines

p1. Simple air injection - Air injected at controlled rate into each engine exhaust port.

p2. Thermal reactors - Air injection thermal reactor installed in place of, or downstream of, exhaust manifold.

p3. Catalytic reactors for THC and CO control - Air injection catalytic reactor installed in exhaust system. Operation with lead-free or low-lead fuel required.

p4. Direct-Flame Afterburner - Thermal reactor with injection of air and additional fuel installed in exhaust system.

p5. Water injection - Water injected into intake manifold with simultaneous reduction in fuel rate to provide operation at leaner fuel-air ratios.

p6. Positive crankcase ventilation - Current PCV system used with automotive engines applied to aircraft engines. Effective only in combination with one of preceding control methods.

p7. Evaporative emission controls - A group of control methods used singly or in combination to reduce evaporative losses from the fuel system. Control methods commonly include charcoal absorbers and vapor traps in combination with relatively complex valving and fuel flow systems.

II. Methods applicable to future engines

p8. Engine redesign - Coordinated redesign of combustion chamber geometry, compression ratio, fuel distribution system, spark and valve timing, fuel-air ratio, and cylinder wall temperature to minimize emissions while maintaining operational reliability.

TABLE 12A

EMISSION CONTROL METHOD EFFECTIVENESS: TURBINE ENGINE MODIFICATIONS

Control Method t1 - Combustion Chamber Redesign (minor)

Best current emission rates assumed to be attainable through minor combustor redesign (lb/1000 lb fuel)

Engine Class	Pollutant	Mode		
		Idle/Taxi	Approach	Take-Off
T1	CO	25	5	2
	THC	10	1	0.2
	NOx	3	7	11
	DP	0.2	0.5	0.5
T2	CO	45	6	1
	THC	10	1	0.1
	NOx	2	6	12
	DP	0.2	0.5	0.5
T3	CO	50	3	0.5
	THC	10	1	0.1
	NOx	3	10	40
	DP	0.1	0.1	0.1

Basis for estimates

It is assumed that emission rates for all engines within a given class can be reduced to common, optimum levels (on a lb/1000 lb fuel basis) by minor combustor modifications. These optimum emission rates are based on the best performance reported for each engine class, excluding extreme data points, as shown in Figures 1-4.

TABLE 12B

EMISSION CONTROL METHOD EFFECTIVENESS: TURBINE ENGINE MODIFICATIONS

Control Method t2 - Combustion Chamber Redesign (major)

Emission Rate with Control Method Installed (as fraction of best current rate for engine class)

Engine Class	Pollutant	Mode Idle/Taxi	Approach	Take-Off
T1	DP	0.5	0.5	0.5
T2	DP	0.5	0.5	0.5

Basis for estimates

Estimates based on reports of carbureting fuel injector performance and reduction of smoke emission. Concept is incorporated in some Class T3 engines. Estimates based on assumption that best emission rate for Class T1 and T2 engines is at visibility threshold at maximum power. Carburetion appears to reduce smoke level, and presumably particulate emissions, to approximately one-half that level (Refs 12 and 13).

TABLE 12C

EMISSION CONTROL METHOD EFFECTIVENESS: TURBINE ENGINE MODIFICATIONS

Control Method t3 - Fuel Drainage Control

Emission Rate with Control Method Installed (as fraction of best current rate for engine class)

Engine Class	Pollutant	Mode Idle/Taxi	Mode Approach	Take-Off (Drainage Mode)
T1	THC			0
T2	THC	no change		0
T3	THC			0

Basis for estimates

Estimate based on the assumption that fuel drainage can be completely eliminated by collecting drained fuel and returning to fuel tank.

TABLE 12D

EMISSION CONTROL METHOD EFFECTIVENESS:
TURBINE ENGINE MODIFICATIONS

Control Method t4 - Divided Fuel Supply System

Emission Rate with Control Method Installed (as fraction of best current rate for engine class)

Engine Class	Pollutant	Mode Idle/Taxi	Approach	Take-Off
T1	CO	0.25	no change	
T1	THC	0.25		
T2	CO	0.25		
T2	THC	0.25		
T3	CO	0.25		
T3	THC	0.25		

Basis for estimates

Control method results in combustion zone fuel-air ratio similar to that at approach condition. Reduction in CO and THC from idle to approach is approximately 90 per cent. Effectiveness reduced by one order because combustor is not operating at a "well-designed condition.

TABLE 12E

EMISSION CONTROL METHOD EFFECTIVENESS: TURBINE ENGINE MODIFICATIONS

Control Method t5 - Water Injection

Emission Rate with Control Method Installed (as fraction of best current rate for engine class)

Engine Class	Pollutant	Mode Idle/Taxi	 Approach	 Take-Off
T1	NOx	no change		0.25
T2	NOx			0.25
T3	NOx			0.25

Basis for estimates

Assumed that water injection used at take-off only and at a rate equal to twice the fuel rate. Also assumed that water is injected into compressor or diffuser by system similar to those in current use. Effectiveness based upon published results with steam injection (Ref 14). Water injection assumed to be of equal effectiveness when injected upstream of combustor.

TABLE 12F

EMISSION CONTROL METHOD EFFECTIVENESS: TURBINE ENGINE MODIFICATIONS

Control Method t6 - Modify Compressor Air Bleed Rate

Emission Rate with Control Method Installed (as fraction of best current rate for engine class)

Engine Class	Pollutant	Mode Idle/Taxi	Approach	Take-Off
T1	CO	0.5	no change	
T1	THC	0.5		
T2	CO	0.5		
T2	THC	0.5		
T3	CO	0.5		
T3	THC	0.5		

Basis for estimates

Assumed that fraction of air which can be bled is small so that engine operating point is nearly unchanged. Assumed that combustor f/a varies inversely with air bleed rate, and that CO and THC emissions at idle vary as:

$$[\mathrm{CO}],\ [\mathrm{THC}] \sim (f/a)^{-3} \sim (\dot{m}_a)^3$$

This relationship based upon data from NREC Report 1134-1 (Ref 1). If maximum air bleed rate is 20 per cent, CO and THC emission rates are reduced by 50 per cent.

TABLE 12G

EMISSION CONTROL METHOD EFFECTIVENESS: TURBINE ENGINE MODIFICATIONS

Control Method t7 - Variable-Geometry Combustion Chamber
or t8 - Staged Injection Combustor

Emission Rate with Control Method Installed (as fraction of best current rate for engine class)

Engine Class	Pollutant	Mode Idle/Taxi	Approach	Take-Off
T1	CO	0.1	NC	NC
	THC	0.1	NC	NC
	NOx	NC	NC	0.5
	DP	0.5	0.5	0.5
T2	CO	0.1	NC	NC
	THC	0.1	NC	NC
	NOx	NC	NC	0.5
	DP	0.5	0.5	0.5
T3	CO	0.1	NC	NC
	THC	0.1	NC	NC
	NOx	NC	NC	0.5
	DP	0.5	0.5	0.5

Basis for estimates:

a. Assumed that combustor primary zone operates at a constant f/a equal to normal f/a at approach power condition (primary zone equivalence ratio = 0.6). CO and THC emissions at idle reduced to levels corresponding to approach power, or by 90 per cent.

b. Combustor incorporates design characteristics which provide well-mixed combustion zone. This feature and constant f/a operation combine to reduce NO emissions at full power by 50 per cent (Ref 16) and particulate emissions by 50 per cent at all power levels as in control method t2.

TABLE 13

CURRENT UNCONTROLLED EMISSION RATES - PISTON ENGINES (lb/1000 lb-fuel)

			Mode	
Pollutant	Idle	Taxi	Approach	Take-Off
CO	896	882	918	849
THC	48	76	80	18
NOx (as NO_2)	7	4	4	6

Basis for Estimates:

Rates listed are average rates for nine engines measured during aircraft operations (Ref 3). Total hydrocarbon (THC) emission rates have been increased by 50 per cent to account for crankcase blow-by emissions. Evaporative emissions are not included in these rates.

TABLE 14

EMISSION CONTROL EFFECTIVENESS: PISTON ENGINE MODIFICATIONS

Control Method	Controlled Emission Rate* (fraction of uncontrolled rate)		
	CO	THC (exhaust only)	Lead
p1 - Simple Air Injection	0.5	0.5	NC
p2 - Thermal Reactor	0.25	0.25	NC
p3 - Catalytic Reactor	0.25	0.25	0.1
p4 - Direct-Flame Afterburner	0.1	0.1	NC
p5 - Water Injection	0.25	0.24	NC
p6 - Positive Crankcase Ventilation	NC	**	NC
p7 - Evaporative Emission Control	NC	***	NC
p8 - Engine Redesign	0.5	0.5	NC

Basis for Estimates

Review of published results on effectiveness of automotive emission controls; in particular, References 17, 18, and 19.

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* Fractions listed are considered to be applicable to all operating modes.

** PCV would eliminate blow-by emissions when used in combination with p1, p2, p3, p4, or p5. Blow-by THC emission estimated to be equal to 30 per cent of uncontrolled exhaust emission.

*** Evaporative controls would reduce THC emissions due to evaporation from fuel supply. Magnitude of uncontrolled emissions is unknown.

TABLE 15

TOTAL AIRCRAFT TURBINE ENGINE DEVELOPMENT COST/TIME SAMPLE CALCULATION

Engine	No. Engines	Control Method	Dev. Cost	Dev. Time	Test Cost	Test Time	Total Dev. & Test Cost	Total Dev. & Test Time	Tool Design Cost	Tool Design Time	Tool Procure Cost	Tool Procure Time	Total Tool Cost	Total Tool Time	Total Dev. & Test & Tool Cost	Total Dev. & Test & Tool Time	No. of Engine Families in Class T 2	Total Dev. Cost Per Class T 2
			$/FAM	yrs.	$/FAM	yrs.	$/FAM	yrs.	$/FAM	yrs.	$/FAM	yrs.	$/FAM	yrs.	$/FAM	yrs.	-	$
JT8D	3191	t_1	360^k	1-2	360^k	1-2	720^k	2-4	120^k	$\frac{1}{4}-\frac{1}{2}$	10^k 60^k	$\frac{1}{4}-\frac{1}{2}$	130^k 180^k	$\frac{1}{2}-1$	900^k	$2\frac{1}{2}-5$	20	18^m
JT8D	3191	t_2	720^k	2-3	720^k	2-3	1.44^m	4-6	240^k	$\frac{1}{2}$-3/4	20^k 120^k	$\frac{1}{2}$-3/4	260^k 360^k	$1-1\frac{1}{2}$	1.8^m	$5-7\frac{1}{2}$	20	36^m
JT8D	3191	t_3	360^k	1-2	360^k	1-2	720^k	2-4	180^k	$\frac{1}{2}$-3/4	15^k 90^k	$\frac{1}{2}$-3/4	195^k 270^k	$1-1\frac{1}{2}$	990^k	$3-5\frac{1}{2}$	20	20^m
JT8D	3191	t_4	720^k	2-3	720^k	2-3	1.44^m	4-6	240^k	$\frac{1}{2}$-3/4	20^k 120^k	$\frac{1}{2}$-3/4	260^k 360^k	$1-1\frac{1}{2}$	1.8^m	$5-7\frac{1}{2}$	20	36^m
JT8D	3191	t_5	200^k	1	360^k	1-2	560^k	2-3	50^k	$\frac{1}{4}-\frac{1}{2}$	5^k 10^k	$\frac{1}{4}-\frac{1}{2}$	55^k 60^k	$\frac{1}{2}-1$	620^k	$2\frac{1}{2}-4$	20	12^m
JT8D	3191	t_6	1080^k	1-2	720^k	2-3	1.8^m	3-5	240^k	$\frac{1}{2}$-3/4	20^k 120^k	$\frac{1}{2}$-3/4	260^k 360^k	$1-1\frac{1}{2}$	2.2^m	$4-6\frac{1}{2}$	20	43^m

TABLE 16

TURBINE ENGINE DEVELOPMENT COST/TIME SAMPLE CALCULATION FOR SEPARATE CATEGORIES; AIR CARRIER, GENERAL AVIATION, MILITARY

Note: Civil Aviation Engines = Sum of Air Carrier and General Aviation Engines

Engine	Control Method	Total Development and Test and Tool Cost	Number of Air Carrier Engine Families in Class T2	Total Development Cost for Class T2 Air Carrier Engines	Number of General Aviation Families in Class T2	Total Development Cost for Class T2 General Aviation Engines	Number of Civil Aviation Engine Families in Class T2	Total Development Cost for Class T2 Civil Aviation Engines	Number of Military Aviation Engine Families in Class T2	Total Development Cost for Class T2 Military Aviation Engines
--	--	$/FAMILY	--	$	--	$	--	$	--	$
JT8D	t_1	900^k	10	9^m	2	1.8^m	12	10.8^m	8	7.2^m
JT8D	t_2	1.8^m	10	18^m	2	3.6^m	12	21.6^m	8	14.4^m
JT8D	t_3	990^k	10	9.9^m	2	2.0^m	12	11.9^m	8	8.1^m
JT8D	t_4	1.8^m	10	18^m	2	3.6^m	12	21.6^m	8	14.4^m
JT8D	t_5	620^k	10	6.2^m	2	1.2^m	12	7.4^m	8	4.6^m
JT8D	t_6	2.2^m	10	22.0^m	2	4.4^m	12	26.4^m	8	16.6^m

TABLE 17

TOTAL AIRCRAFT PISTON ENGINE DEVELOPMENT COST/TIME SAMPLE CALCULATION

Engine	Control Method	Dev. Cost	Dev. Time	Test Cost	Test Time	Total Dev. & Test Cost	Total Dev. & Test Time	Tool Design Cost	Tool Design Time	Tool Procure Cost	Tool Procure Time	Total Tool Cost	Total Tool Time	Per Family Total One-Time Cost	Total Time Dev. & Test Tool	No. of Engines Families in Class PI	Total Dev. Cost for Class PI
--	--	$	yrs	$	yrs.	$	yrs.	$	yrs.	$	yrs.	$	yrs.	$	yrs	--	--
Piston	P_1	62^k	½-1	170^k	½-1	232^k	1-2	30^k	¼-½	10^k	¼-½	40^k	½-1	272^k	1½-3	35	9.5M
Piston	P_2	228^k	1-2	350^k	1-2	578^k	2-4	120^k	½-1	30^k	½-1	150^k	1-2	728^k	3-6	35	25.6M
Piston	P_3	216^k	1-2	350^k	1-2	566^k	2-4	60^k	¼-½	15^k	¼-½	75^k	½-1	641^k	2½-5	35	22.4M
Piston	P_4	228^k	1-2	350^k	1-2	578^k	2-4	120^k	½-¼	30^k	½-1	150^k	1-2	728^k	3-6	35	25.6M
Piston	P_5	61^k	½-1	170^k	½-1	231^k	1-2	15^k	¼-½	5^k	¼-½	20^k	½-1	251^k	1½-3	35	8.8M
Piston	P_6	--	--	95^k	½-1	95^k	½-1	5^k	¼-½	5^k	¼-½	10^k	½-1	105^k	1-2	35	3.7M
Piston	P_7	47^k	½/3/4	70^k	½-3/4	117^k	1-1½	5^k	¼-½	5^k	¼-½	10^k	½-1	127^k	1½-2½	35	4.5M

TABLE 18

PISTON ENGINE DEVELOPMENT COST/TIME SAMPLE CALCULATION FOR SEPARATE CATEGORIES; AIR CARRIER, GENERAL AVIATION, MILITARY

Note: Civil Aviation Engines = Sum of Air Carrier and General Aviation Engines

Control Method	Total Develop-ment and Test and Tool Cost	Number of Air Carrier Engine Families in Class PI	Total Develop-ment Cost for Class PI Air Carrier Engines	Number of General Aviation Families in Class PI	Total Develop-ment Cost for Class PI General Aviation Engines	Number of Civil Aviation Engine Families in Class PI	Total Develop-ment Cost for Class PI Civil Aviation Engines	Number of Military Aviation Engine Families in Class PI	Total Develop-ment Cost for Class PI Military Aviation Engines
--	\$/FAMILY	--	\$	--	\$	--	\$	--	\$
P_1	272^k	0^*	0	34	9.3^m	34	9.3^m	1	272^k
P_2	728^k	0	0	34	24.8^m	34	24.8^m	1	728^k
P_3	691^k	0	0	34	21.7	34	21.7^k	1	641^k
P_4	728^k	0	0	34	24.8^m	34	24.8^m	1	728^k
P_5	251^k	0	0	34	8.5^m	34	8.5^m	1	251^k
P_6	105^k	0	0	34	3.6^m	34	3.6^m	1	105^k
P_7	127^k	0	0	34	4.3^m	34	4.3^m	1	127^k

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* Air carrier piston engines not included.

TABLE 19

TOTAL AIRCRAFT TURBINE ENGINE IMPLEMENTATION COST/TIME SAMPLE CALCULATION

Engine	Control Method	Lost Service Life Cost/ Engine	Add. Instal-lation Cost/ Engine	10 Years Total Add. Instal-lation Cost/ Engine	Continu-ing Add. Cost/ Engine/ Year	10 Years Continu-ing Add. Cost/ Engine	10 Years Total Imple-ment Cost/ Engine	Total No. of Engines in Class T 2	10 Years Total Imple-ment Cost for Class T2 Engines	Total Time Between Over-hauls (TBO)	Imple-ment Start Date	Imple-ment Finish Date
--	--	$/Eng	$/Eng	$/Eng	$/Eng/Yr	$/Eng	$/Eng	--	$\$\times 10^6$	Yrs.	--	--
JT8D	t_1	2500	2000	8000	2500	25000	35500	35874	1275	2 1/2	1977	1979
JT8D	t_2	2500	4000	16000	4240	42400	60900	35874	2180	2 1/2	1979	1983
JT8D	t_3	500	1000	4000	0	0	4500	35874	161	2 1/2	1977	1980
JT8D	t_4	2500	2000	8000	0	0	10500	35874	376	2 1/2	1979	1982
JT8D	t_5	0	2000	8000	760	7600	15600	35874	560	2 1/2	1976	1978
JT8D	t_6	0	1500	6000	0	0	6000	35874	215	2 1/2	1978	1981

TABLE 20

TURBINE ENGINE IMPLEMENTATION COST/TIME SAMPLE CALCULATION FOR SEPARATE CATEGORIES: AIR CARRIER, GENERAL AVIATION, MILITARY

Note: Civil Engines = Sum of Air Carrier and General Aviation Engines

Engine	Control Method	10 Years Total Implementation Cost/Engine	Number of Air Carrier Engines in Class T2	Total Implement Cost for Class T2 Air Carrier Engines	Number of General Aviation Engines in Class T2	Total Implement Cost for Class T2 General Aviation Engines	Number of Civil Aviation Engines in Class T2	Total Implement Cost for Class T2 Civil Aviation Engines	Number of Military Aviation Engines in Class T2	Total Implement Cost for Class T2 Military Aviation Engines
--	--	$/ENG	--	$\$\times10^{-6}$	--	$\$\times10^{-6}$	--	$\$\times10^{-6}$		$\$\times10^{-6}$
JT8D	t_1	35,500	6,576	233	448	16	7,024	250	28,850	1,025
JT8D	t_2	60,900	6,576	400	448	27	7,024	428	28,850	1,752
JT8D	t_3	4,500	6,576	30	448	2	7,024	32	28,850	129
JT8D	t_4	10,500	6,576	69	448	5	7,024	74	28,850	302
JT8D	t_5	15,600	6,576	103	448	7	7,024	110	28,850	450
JT8D	t_6	6,000	6,576	39	448	3	7,024	42	28,850	173

TABLE 21

TOTAL AIRCRAFT PISTON ENGINE IMPLEMENTATION COST/TIME SAMPLE CALCULATION

Engine	Control Method	Lost Service Life Cost/ Engine	Add. Installation Cost/ Engine	10 Years Total Add. Installation Cost/ Engine	Continuing Add. Cost/ Engine/ Year	10 Years Continuing Add. Cost/ Engine	10 Years Total Implement Cost/ Engine	Total No. of Engines in Class PI	10 Years Total Implement Cost for Class PI Engines	Total Time Between Overhauls (TBO)	Implement Start Date	Implement Finish Date
--	--	\$/Eng	\$/Eng	\$/Eng	\$/Eng/Yr	\$/Eng	\$/Eng	--	$\$ \times 10^6$	Yrs.	--	--
Piston	P_1	25	450	900	30	300	1225	136,166	167	5	1975	1980
Piston	P_2	25	850	1700	142	1420	3145	136,166	430	5	1978	1983
Piston	P_3	25	825	1650	230	2300	3975	136,166	542	5	1977	1982
Piston	P_4	25	850	1700	142	1420	3145	136,166	430	5	1978	1983
Piston	P_5	0	300	600	0	0	600	136,166	82	5	1975	1980
Piston	P_6	0	150	200	50	500	700	136,166	96	5	1974	1979
Piston	P_7	0	500	1000	100	1000	2000	136,166	272	5	1974	1979

TABLE 22

PISTON ENGINE IMPLEMENTATION COST/TIME SAMPLE CALCULATION FOR SEPARATE CATEGORIES: AIR CARRIER, GENERAL AVIATION, MILITARY

Note: Civil Engines = Sum of Air Carrier and General Aviation Engines

Control Method	10 Years Total Implementation Cost/ Engine	Number of Air Carrier Engines in Class PI	Total Implement Cost for Class PI Air Carrier Engines	Number of General Aviation Engines in Class PI	Total Implement Cost for Class PI General Aviation Engines	Number of Civil Aviation Engines in Class PI	Total Implement Cost for Class PI Civil Aviation Engines	Number of Military Aviation Engines in Class PI	Total Implement Cost for Class PI Military Aviation Engines
--	\$/ENG	--	$\$\times10^{-6}$	--	$\$\times10^{-6}$	--	$\$\times10^{-6}$	--	$\$\times10^{-6}$
P_1	1,225	0	0	134,760	165	134,760	165	1,406	1.7
P_2	3,145	0	0	134,760	424	134,760	424	1,406	4.4
P_3	3,975	0	0	134,760	536	134,760	536	1,406	5.6
P_4	3,145	0	0	134,760	424	134,760	424	1,406	4.4
P_5	600	0	0	134,760	81	134,760	81	1,406	0.8
P_6	700	0	0	134,760	95	134,760	95	1,406	1.0
P_7	2,000	0	0	134,760	270	134,760	270	1,406	2.8

TABLE 23

TURBINE ENGINE COST SCALING PARAMETER SUMMARY

Engine	SFC lb/HP-HR	OPR P_2/P_1	W (lbs)	T(P) lbs(ESHP)	SFC×OPR	2W/T	P	P/P_*	10 Year Total Implement Cost/ Engine $/ENG.	$\frac{\sqrt{T}}{\sqrt{lbs}}$	$\sqrt{T}/\sqrt{T_*}$	10 Year Total Implement Cost/ Engine $/ENG.
--					--	--		--				
T53	0.56	8	561	1900	4.48	0.59	5.07	0.43	15250	43.6	0.35	12400
* JT8D	0.63	18	3309	15500	11.35	0.43	11.78	1.00	35500	125	1.00	35500
TF39	0.58	25.7	7311	41100	14.95	0.36	15.31	1.30	46200	205	1.64	58300

$$P = \text{Technical Scaling Parameter} = \left[(SFC \times OPR) + \frac{2W}{T}\right]$$

SFC = Specific Fuel Consumption
OPR = Over-All Pressure Ratio
W = Engine Dry Weight
T = Engine Thrust

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* Baseline Engine

TABLE 24

FINAL COST/TIME RESULTS FOR TOTAL TURBINE ENGINE POPULATION

Cost Scaling Factor	Engine Class	Baseline Engine	Control Method	Total Families	Total Engines	Total Dev. and Implement Cost, $	Total Dev. and Implement Time, yrs
0.35	T 1	T53	t_1	42	48,773	643.0M	5-7½
0.35	T 1	T53	t_2	42	48,773	1116.0M	7½-10
0.35	T 1	T53	t_3	42	48,773	120.0M	5½-8
0.35	T 1	T53	t_4	42	48,773	257.0M	7½-10
0.35	T 1	T53	t_5	42	48,773	295.0M	5-6½
0.35	T 1	T53	t_6	42	48,773	196.0M	6½-9
1.00	T 2	JT8D	t_1	20	35,874	1293.0M	5-7½
1.00	T 2	JT8D	t_2	20	35,874	2226.0M	7½-10
1.00	T 2	JT8D	t_3	20	35,874	181.0M	5½-8
1.00	T 2	JT8D	t_4	20	35,874	412.0M	7½-10
1.00	T 2	JT8D	t_5	20	35,874	572.0M	5-6½
1.00	T 2	JT8D	t_6	20	35,874	258.0M	6½-9
1.64	T 3	TF39	t_1	9	322	26.8M	5-7½
1.64	T 3	TF39	t_2	9	322	48.4M	7½-10
1.64	T 3	TF39	t_3	9	322	11.3M	5½-8
1.64	T 3	TF39	t_4	9	322	21.7M	7½-10
1.64	T 3	TF39	t_5	9	322	13.9M	5-6½
1.64	T 3	TF39	t_6	9	322	23.0M	6½-9
	$\Sigma_T = T1 + T2 + T3$		t_1	71	84,969	1963M	5-7½
	$\Sigma_T = T1 + T2 + T3$		t_2	71	84,969	3390M	7½-10
	$\Sigma_T = T1 + T2 + T3$		t_3	71	84,969	312M	5½-8
	$\Sigma_T = T1 + T2 + T3$		t_4	71	84,969	691M	7½-10
	$\Sigma_T = T1 + T2 + T3$		t_5	71	84,969	881M	5-6½
	$\Sigma_T = T1 + T2 + T3$		t_6	71	84,969	477M	6½-9

TABLE 25 (CONTINUED)

FINAL COST/TIME RESULTS FOR TURBINE ENGINE POPULATION BY SEPARATE CATEGORIES: AIR CARRIER, GENERAL AVIATION, MILITARY

Engine Class	Control Method	Cost Scaling Factor	Development Cost Per Family	Implement Cost Per Engine	Air Carrier Total Cost	General Aviation Total Cost	Civil Aviation Total Cost	Military Aviation Total Cost
T3	t_5	1.64	0.62	25.6	5.9	0.0	5.9	7.8
T3	t_6	1.64	2.20	9.9	16.0	0.0	16.0	7.0
ET=T1+T2 +T3	t_1	--	--	--	272.0	108.0	380.0	1583.0
ET=T1+T2 +T3	t_2	--	--	--	472.0	192.0	664.0	2726.0
ET=T1+T2 +T3	t_3	--	--	--	54.0	29.0	83.0	229.0
ET=T1+T2 +T3	t_4	--	--	--	116.0	61.0	177.0	514.0
ET=T1+T2 +T3	t_5	--	--	--	125.0	52.0	177.0	704.0
ET+T1+T2 +T3	t_6	--	--	--	93.0	55.0	148.0	329.0

TABLE 25

FINAL COST/TIME RESULTS FOR TURBINE ENGINE POPULATION BY SEPARATE CATEGORIES: AIR CARRIER, GENERAL AVIATION, MILITARY

Note: Civil Engine = Sum of Air Carrier and General Aviation Engines

Engine Class	Control Method	Cost Scaling Factor	Development Cost Per Family	Implement Cost Per Engine	Air Carrier Total Cost	General Aviation Total Cost	Civil Aviation Total Cost	Military Aviation Total Cost
			$\$/\text{FAM}\times10^{-6}$	$\$/\text{ENG}\times10^{-3}$	$\$\times10^{-6}$	$\$\times10^{-6}$	$\$\times10^{-6}$	$\$\times10^{-6}$
--	--	--			19.2	90.5	109.7	533.0
T1	t_1	0.35	0.90	12.4	34.5	159.3	193.8	921.0
T1	t_2	0.35	1.80	21.3	7.7	25.6	33.5	87.0
T1	t_3	0.35	0.99	1.6	14.9	51.5	66.4	190.0
T1	t_4	0.35	1.80	3.7	9.8	43.6	53.4	240.0
T1	t_5	0.35	0.62	5.5	15.5	48.1	63.6	131.0
T1	t_6	0.35	2.20	2.1	243.0	17.8	259.8	1032.2
T2	t_1	1.00	0.90	35.5	418.0	31.0	449.6	1774.4
T2	t_2	1.00	1.80	69.9	39.5	4.0	43.5	137.9
T2	t_3	1.00	0.99	4.5	87.0	8.3	95.3	317.4
T2	t_4	1.00	1.80	10.5	108.7	8.2	116.9	454.9
T2	t_5	1.00	0.62	15.6	61.5	7.1	68.6	190.6
T2	t_6	1.00	2.20	6.0	10.0	0.0	10.0	16.8
T3	t_1	1.64	0.90	58.3	19.0	0.0	19.0	29.4
T3	t_2	1.64	1.80	100.0	7.4	0.0	7.4	3.9
T3	t_3	1.64	0.99	7.4	13.7	0.0	13.7	8.0
T3	t_4	1.64	1.80	17.2				

TABLE 25 (CONTINUED)

FINAL COST/TIME RESULTS FOR TURBINE ENGINE POPULATION BY SEPARATE CATEGORIES: AIR CARRIER, GENERAL AVIATION, MILITARY

Engine Class	Control Method	Cost Scaling Factor	Development Cost Per Family	Implement Cost Per Engine	Air Carrier Total Cost	General Aviation Total Cost	Civil Aviation Total Cost	Military Aviation Total Cost
T3	t_5	1.64	0.62	25.6	5.9	0.0	5.9	7.8
T3	t_6	1.64	2.20	9.9	16.0	0.0	16.0	7.0
ET=T1+T2 +T3	t_1	--	--	--	272.0	108.0	380.0	1583.0
ET=T1+T2 +T3	t_2	--	--	--	472.0	192.0	664.0	2726.0
ET=T1+T2 +T3	t_3	--	--	--	54.0	29.0	83.0	229.0
ET=T1+T2 +T3	t_4	--	--	--	116.0	61.0	177.0	514.0
ET=T1+T2 +T3	t_5	--	--	--	125.0	52.0	177.0	704.0
ET+T1+T2 +T3	t_6	--	--	--	93.0	55.0	148.0	329.0

TABLE 26

FINAL COST/TIME RESULTS FOR TOTAL PISTON ENGINE POPULATION

Cost Scaling Factor	Engine Class	Baseline Engine	Control Method	Total Families	Total Engines	Total Dev. and Implement Cost, $	Total Dev. and Implement Time, yrs
1.00	PI	Aircraft Piston	P_1	35	136,166	176.5M	6½-8
1.00	PI	Aircraft Piston	P_2	35	136,166	453.6M	8-11
1.00	PI	Aircraft Piston	P_3	35	136,166	564.4M	7½-10
1.00	PI	Aircraft Piston	P_4	35	136,166	453.6M	8-11
1.00	PI	Aircraft Piston	P_5	35	136,166	90.8M	6½-8
1.00	PI	Aircraft Piston	P_6	35	136,166	98.7M	6-7
1.00	PI	Aircraft Piston	P_7	35	136,166	276.5M	6½-7½

TABLE 27

FINAL COST/TIME RESULTS FOR PISTON ENGINE POPULATION BY SEPARATE CATEGORIES: AIR CARRIER, GENERAL AVIATION, MILITARY

Note: Civil Engine = Sum of Air Carrier and General Aviation Engines

Engine Class	Control Method	Cost Scaling Factor	Development Cost Per Family	Implement Cost Per Engine	Air Carrier Total Cost	General Aviation Total Cost	Civil Aviation Total Cost	Military Aviation Total Cost
--	--	--	$\$/FAM\times10^{-6}$	$\$/ENG\times10^{-3}$	$\$\times10^{-6}$	$\$\times10^{-6}$	$\$\times10^{-6}$	$\$\times10^{-6}$
PI	P_1	1.00	0.27	1.23	0.0	174.5	174.5	2.0
PI	P_2	1.00	0.73	3.15	0.0	448.4	443.4	5.2
PI	P_3	1.00	0.64	3.98	0.0	556.8	556.8	6.3
PI	P_4	1.00	0.73	3.15	0.0	448.7	448.4	5.2
PI	P_5	1.00	0.25	0.60	0.0	89.7	89.7	1.1
PI	P_6	1.00	0.11	0.70	0.0	97.6	97.6	1.1
PI	P_7	i.00	0.13	2.00	0.0	273.3	273.3	3.0

TABLE 28

IMPLEMENTATION COST/TIME SAMPLE CALCULATION FOR "PRODUCTION" TURBINE ENGINES OF EXISTING DESIGN

Engine	Control Method	Additional Installation Cost Per Engine	10 Years Total Additional Installation Cost Per Engine	Continuing Additional Cost/Engine/Year	10 Years Continuing Additional Cost Per Engine	10 Years Total Implementation Cost Per Engine	Effective Production Start Date*
		\$/Eng x 10^{-3}	\$/Eng x 10^{-3}	\$/Eng/Yr x 10^{-3}	\$/Eng x 10^{-3}	\$/Eng x 10^{-3}	
JT8D	t_1	1.0	4.0	2.5	25.0	29.0	1977
JT8D	t_2	3.0	12.0	4.24	42.4	54.4	1979
JT8D	t_3	0.5	2.0	0	0	2.0	1977
JT8D	t_4	1.5	6.0	0	0	6.0	1979
JT8D	t_5	1.8	7.2	0.76	3.0	10.2	1976
JT8D	t_6	1.0	4.0	0	0	4.0	1978

---

* This date assumes the control system development effort is initiated 1/1/72 and that the maximum development, testing, and tooling time is required, as tabulated in Table 15.

TABLE 29

IMPLEMENTATION COST/TIME SAMPLE CALCULATION FOR "PRODUCTION" PISTON ENGINES OF EXISTING DESIGN

Engine	Control Method	Additional Installation Cost Per Engine	10 Years Total Additional Installation Cost Per Engine	Continuing Additional Cost/Engine/Year	10 Years Continuing Additional Cost Per Engine	10 Years Total Implementation Cost Per Engine	Effective Production Start Date*
		\$/Eng x 10^{-3}	\$/Eng x 10^{-3}	\$/Eng/Yr x 10^{3}	\$/Eng x 10^{-3}	\$/Eng x 10^{-3}	
Piston	P_1	0.200	0.400	0.030	0.30	0.70	1975
Piston	P_2	0.500	1.000	0.142	1.42	2.42	1978
Piston	P_3	0.475	0.950	0.230	2.30	3.25	1977
Piston	P_4	0.500	1.000	0.142	1.42	2.42	1978
Piston	P_5	0.150	0.300	0	0	0.30	1975
Piston	P_6	0.075	0.150	0.050	0.50	0.65	1974
Piston	P_7	0.100	0.200	0.100	1.00	1.20	1974

---

* This date assumes the control system development effort is initiated 1/1/72 and that the maximum development, testing, and tooling time is required, as tabulated in Table 17.

TABLE 30

IMPLEMENTATION COST/TIME FINAL RESULTS FOR "PRODUCTION" ENGINES-TURBINE AND PISTON ENGINES OF EXISTING DESIGN

Engine Class	Control Method	Scaling Factor	10 Year Total Implementation Cost Per Engine $/Eng	Implementation Start Date
T1	t_1	0.35	101,50	1977
T1	t_2	0.35	19,000	1979
T1	t_3	0.35	700	1977
T1	t_4	0.35	2,100	1979
T1	t_5	0.35	3,570	1976
T1	t_6	0.35	1,400	1978
T2	t_1	1.00	29,000	1977
T2	t_2	1.00	54,400	1979
T2	t_3	1.00	2,000	1977
T2	t_4	1.00	6,000	1979
T2	t_5	1.00	10,200	1976
T2	t_6	1.00	4,000	1978
T3	t_1	1.64	47,600	1977
T3	t_2	1.64	89,200	1979
T3	t_3	1.64	3,280	1977
T3	t_4	1.64	9,840	1979
T3	t_5	1.64	16,700	1976
T3	t_6	1.64	6,560	1978
P1	P_1	1.00	700	1975
P1	P_2	1.00	2,420	1978
P1	P_3	1.00	3,250	1977
P1	P_4	1.00	2,420	1978
P1	P_5	1.00	300	1975
P1	P_6	1.00	650	1974
P1	P_7	1.00	1,200	1974

TABLE 31

COST/TIME RESULTS FOR FUTURE TURBINE ENGINES

Item	Unit	New Combustor of Current Type	Variable Geometry Combustor	Staged Injection Combustor
Design Cost	$	150K	300K	550K
Prototype Hardware Cost	$	180K	280K	360K
Testing Cost	$	620K	740K	850K
Cost of Incorporation of Prototype Design into Demonstrator Engine	$	850K	1000K	900K
Total Demonstrator Engine Development Cost	$	1800K	2240K	2660K
Prototype Development Time	Yrs	2.0	3.5	5.0
Fraction of Development Cost Attributable to Emission Control	%	0.0	34	47
Fraction of Development Time Attributable to Emission Control	%	0.0	43	60
Fraction of Engine Purchase Price from Combustor	%	4.5	8.5	7.0

TABLE 32

REDUCTION IN EMISSION FACTORS FOR 100 PER CENT INCREASE IN IDLE POWER

		Pollutant			
		CO		Hydrocarbons	
Aircraft Class	Average Number of Engines per Aircraft	Uncontrolled Idle Emissions Per Engine Grams Per Hour	Controlled Emissions As Per Cent Of Uncontrolled Emissions	Uncontrolled Idle Emissions Per Engine Grams Per Hour	Controlled Emissions As Per Cent Of Uncontrolled Emissions
2	4	427000	58	10500	108
3	4	68600	62	30800	91
4	2.6	26000	62	3540	71
5	2.5	5800	20	1900	30
6	2.1	26700	59	3130	61

TABLE 33

REDUCTION IN TAXI AND IDLE EMISSIONS RESULTING FROM THE USE OF THE MINIMUM NUMBER OF ENGINES FOR TAXIING

Aircraft Class	Number of Engines	Controlled Emission Rate as a Per Cent of Uncontrolled Emission Rate	
		CO	Hydrocarbons
2	4 to 2	29	54
3	4 to 2	31	45
4	3 to 2	42	48
	2 to 2	62	71
	2.6 to 2 mean	48	55
5	4 to 2	10	15
	2 to 2	20	30
	2.5 to 2 mean	16	24
6	4 to 2	30	30
	2 to 2	59	61
	2.1 to 2 mean	56	58
2	4 to 1	15	27
3	4 to 1	15	22
4	3 to 1	21	24
	2 to 1	31	35
	2.6 to 1 mean	24	27
5	4 to 1	5	7
	2 to 1	10	15
	2.5 to 1 mean	8	12
6	4 to 1	15	15
	2 to 1	30	30
	2.1 to 1 mean	28	29

TABLE 34

TOTAL AIRCRAFT EMISSIONS FOR 1970 AT LOS ANGELES INTERNATIONAL AIRPORT

Pollutant	Approach	Landing	Taxi	Idle & Shut-Down	Main-tenance	Start-up & Idle	Delay at Runway	Take-Off	Climb-Out	Fuel Dump-ing
					grams x 10^{-6}					
CO	704	288	8720	324	864	728	1360	87.1	115	0
NOx	302	1.09	33.2	0.678	50.5	2.27	5.16	246	293	0
SO_2	163	2.81	67.6	2.41	22.5	5.63	10.5	400	444	0
particulates	175	1.25	37.7	10.7	26.2	3.12	5.87	103	118	93.4
lead	0.0205	0.00424	0.153	0.00106	0.0241	0.0127	0.0238	0.0155	0.0502	0
hydrocarbons	843	117	3520	141	426	293	548	29.8	39.1	93.4
reactive hydrocarbons	6.36	0.253	6.06	0.127	0.581	0.505	0.943	4.49	6.10	17.2
aldehydes	111	3.81	108	4.38	13.2	9.01	16.8	2.87	3.22	0

TABLE 35

PERCENTAGE REDUCTION IN TOTAL AIRCRAFT EMISSIONS DUE TO AVOIDING RUNWAY DELAYS AT LOS ANGELES INTERNATIONAL AIRPORT

Pollutant	Delay Mode Emissions Grams Per Year x 10^{-6}	Total Emissions Grams Per Year x 10^{-6}	Controlled Emissions Per Cent Of Un-Controlled Emissions
CO	1360	13200	90
NOx	5.16	934	99.5
SO_2	10.5	1120	99
particulates	5.87	574	99
lead	0.0238	0.305	93
hydrocarbons	548	6060	91
reactive hydrocarbons	0.943	42.7	98
aldehydes	16.8	273	94

TABLE 36

EMISSIONS FOR TAXI MODE

Aircraft	CO	NO_x	SO_2	Alde-hydes	Reactive Hydro-carbons	Total Hydro-carbons	Lead	Partic-ulates
Class 1	45900	612	----	1160	----	200	----	0
Class 2	9770	321	145	39.5	241	2410	----	236
Class 3	15700	15.1	115	222	----	7040	----	46.5
Class 4	3870	34.2	4.13	3.27	----	526	----	48.5
Class 5	829	189	----	----	----	271	----	20.1
Class 6	3210	18.1	87.9	25.0	----	376	----	3.87
Diesel Fuelled Vehicles								
Tractor	439	1030	91.1	6.13	----	51.1	----	20.4

TABLE 37

PERCENTAGE REDUCTION IN TOTAL AIRCRAFT EMISSIONS DUE TO ELIMINATION OF THE TAXI MODE AT LOS ANGELES INTERNATIONAL AIRPORT

Pollutant	Delay Mode Emissions Grams Per Year x 10^{-6}	Total Emissions Grams Per Year x 10^{-6}	Controlled Emissions Per Cent Of Un-Controlled Emissions
CO	8720	13200	34
NOx	33.2	934	96
SO_2	67.6	1120	94
particulates	37.7	574	93
lead	0.153	0.305	50
hydrocarbons	3520	6060	42
reactive hydrocarbons	6.06	42.7	86
aldehydes	108	273	60

TABLE 38

POLLUTANTS FROM AUXILIARY POWER UNIT

Mode	CO	NOx	Hydrocarbons	Particulates
	For Each Mode in Grams			
Taxi	19.7	40.5	27.4	6.84
Park	157	324	219	54.7
Taxi	39.3	81.1	54.7	13.7
Ascent	19.7	40.5	27.4	6.84
Total	236	486	328	82.1

For Los Angeles International Airport For 1970

	CO	NOx	Hydrocarbons	Particulates
Emissions Without APU as a Per Cent of Un-Controlled Emissions	99.5	88	98.5	96

TABLE 39

COMPARATIVE REDUCTIONS RESULTING FROM CONTROL METHODS APPLIED TO LOS ANGELES INTERNATIONAL AIRPORT

Control Method	Controlled Emissions as Per Cent of Uncontrolled Emissions CO	 Hydrocarbons
1. Increase engine idle rpm	71	93
2. Increase idle rpm and use minimal engines for taxi:		
a. two engines	53	66
b. single engine	39	51
3. Eliminate delays at gate and runway	90	91
4. Transport passengers between terminal and aircraft	100	100
5. Tow aircraft to avoid taxi emissions	34	42
6. Avoid use of aircraft auxiliary power units	99.5	98.5
7. Control emptying of fuel drainage reservoirs	100	98.4

TABLE 40

BASIS FOR ESTIMATING COSTS OF GROUND OPERATION CHANGES AT LOS ANGELES INTERNATIONAL AIRPORT

Control Method	Land Cost	Construction Cost	Equipment Cost	Automating Cost	Per Annum Operating Cost Change
Increase Idle Speed	--	--	--	--	Fuel: 600 lb per Engine-Hour at $0.04/lb, 360K Engine-Hours
Minimal Engine Taxi: 2 Engines	--	--	--	--	Save 90K Engine-Hours Add 200 lb per Hour Fuel for 270K Engine-Hours
1 Engine	--	--	--	--	Save 227K Engine-Hours Add 600 lb per Hour Fuel for 133K Engine-Hours
Controlled Gate Departure	18 Acres at $50K per Acre	18 Acres at $500K per Acre	IBM 360/65 $4000K	25 Man-Years $60K per Man-Year	Save 1200 lb-Fuel per Engine-Hour 40K Engine-Hours
Passenger Transport	90 Acres at $50K per Acre	90 Acres at $500 per Acre	75 Vehicles $200K per Vehicle	3 Man-Years $60K per Man-Year	Save 180K Engine-Hours Spend $40K Labor, $20K Fuel per Vehicle
Aircraft Towing	--	--	25 New Vehicles $30K per Vehicle	8 Man-Years $60K per Man-Year	Save 360K Engine-Hours Spend $40K Labor, $20K Fuel per Vehicle Spend 150K Crew Hours
Ground-Based APU	--	--	37 Air Supply at $20K 37 Electrical at $15K	--	Spend $20K Fuel per Vehicle
Fuel Drainage Equipment	--	--	75 Devices at $500	--	Add 75 Man-Years

TABLE 41

IMPLEMENTATION COST AND TIME FOR OPERATIONS CHANGES AT LOS ANGELES INTERNATIONAL AIRPORT

Control Method	Land Cost	Construction Cost	Equipment Cost	Automating Cost	Total Initial Cost	Per Annum Change in Cost of Operation	Time Required
Increase Idle Speed	--	--	--	--	$0	$8500K	Negligible
Minimal Engine Taxi:							
2 Engines	--	--	--	--	$0	-$3000K	4 Months
1 Engine	--	--	--	--	$0	-$7500	1 Year
Controlled Gate Departure	$900K	$9000K	$4000K	$1500K	$15,400K	-$1560	5 Years
Passenger Transport	$4500K	$45,000K	$15,000K	$180K	$64,680K	-$4000 to $5000K	2.5 Years
Aircraft Towing	--	--	$750K	$480K	$1230K	+$417,000	1 Year
Ground-Based APU	--	--	$1295K	--	$1295K	$1500K	6 Months
Fuel Drainage Equipment	--	--	$38K	--	$38K	$3000K	6 Months

TABLE 42

FACTORS AFFECTING FEASIBILITY OF OPERATING CHANGES AT LOS ANGELES INTERNATIONAL AIRPORT

Control Method	Implementation Requires	Advantages Other than Emissions	Constraints and Disadvantages
Increase Idle Speed	1. Pilot Procedure Change	---	1. Limited by Braking Capacity
Minimal Engine Taxi	1. Pilot Procedure Change 2. Fire-Protection at Runway End	1. Use Less Fuel for same thrust	1. Limited by Jet Blast when Starting from Dead Stop
Controlled Gate Departure	1. Automated Traffic Control 2. Interim Parking Area	1. Expedites Airport Traffic	1. Complicated System Requires Continuous Updating .
Passenger Transport	1. Mobile Lounges 2. Parking Area Near Runways	1. Use Less Fuel	1. Requires Airport Expansion
Aircraft Towing	1. Tow Vehicles 2. Revised Schedules	1. Use Less Fuel	1. Requires Much More Taxi Time
Ground-Based APU	1. Air and Electrical Supply Units	---	1. Clutters Parking Area
Fuel Drainage Equipment	1. Equipment and Personnel	---	1. Adds a Task to Aircraft Service Procedure

TABLE 43

CURRENT RANGES OF AIRCRAFT ENGINE EXHAUST EMISSION CONCENTRATIONS

Pollutant Species	Turbine				Piston					
	Idle	Approach	Cruise	Take-Off	Taxi	Idle	Ascent	Cruise Rich	Cruise Lean	Descent
Total Hydrocarbons, ppmC	75-1025	2-280	0-150	0-55	3,000-30,000	2,000-30,000	900-10,000	900-2800	200-1800	900-35,000
CO ppm	100-1600	30-140	0-85	0-70	3%-12%	5%-11%	6%-12%	5%-11%	0.4%-5%	1%-11%
NO ppm	1-10	10-40	10-110	7-125						
NOx ppm (as NO_2)	5-19	10-60	15-165	25-300	70-850	80-1300	90-600	80-700	600-4800	75-750
Dry Part. mg/m^3	0-200	5-150	6-60	2-150						
Total Part. mg/m^3	500-700	300-550	200-550	200-450						
CO_2 (%)	0.9-2.5%	1.4-3.2%	1.5-3.2%	2.0-4.1%	6-12%	6-11%	4-14%	7-13%	11-15%	5-12%
Total Aldehydes ppm	0.9-60	0-20	0-20	0-30		27	16	33	18	51

TABLE 44

INSTRUMENTATION ACCURACY REQUIREMENTS FOR EXHAUST GAS ANALYSIS

Pollutant Species	Recommended Range	Recommended Accuracy
Total Hydrocarbons ppmC	0-10	±5% full scale with propane calibration gas
	0-100	±2% full scale with propane calibration gas
	0-1000	±1% full scale with propane calibration gas
	0-10,000	±1% full scale with propane calibration gas
	0-5%	±1% full scale with propane calibration gas
CO ppm	0-10	±5% full scale
	0-100	±2% full scale
	0-500	±1% full scale
	0-2500	±1% full scale
	0-20,000	±1% full scale
	0-15%	±1% full scale
NO ppm	0-10	±5% full scale
	0-50	±2.5% full scale
	0-250	±2% full scale
	0-1000	±2% full scale
	0-5000	±1% full scale
NOx (as NO_2) ppm	0-10	±5% full scale
	0-50	±2.5% full scale
	0-250	+2% full scale
	0-1000	±2% full scale
	0-5000	±1% full scale
DRK Particulates mg/m3	0-10	±5% full scale
	0-50	±5% full scale
	0-100	±5% full scale
	0-250	±5% full scale
Total Particulates mg/m3	0-100	±5% full scale
	0-1000	±5% full scale
CO_2 (%)	0-2%	±1% full scale
	0-5%	±1% full scale
	0-15%	±1% full scale
	0-20%	±1% full scale
Total Aldehydes (as HCHO)	0-10	±5% full scale
	0-50	±2% full scale
	0-100	±2% full scale

TABLE 45

EXHAUST GAS ANALYSIS METHODS IN USE AT 17 ORGANIZATIONS

Analysis Method	Number Using Method
Carbon Dioxide	
Flame Ionization (after conversion to methane)	(1)
Gas Chromatography	(2)
NDIR	(14)
Carbon Monoxide	
Flame Ionization (after conversion to methane)	(1)
Gas Chromatography	(2)
NDIR	(17)
Hydrocarbons	
Flame Ionization with Heated (~ 350-400 deg F) Sample Line	(8)
Flame Ionization, Unheated ($<$300 deg F line)	(5)
Flame Ionization, Line Temperature not Reported	(5)
High Temperature Oxidation to CO_2 ($<$ 300 deg F line)	(1)
NDIR	(1)
Nitric Oxide	
NDIR	(12)
Saltzmann Method	(2)
PDS	(2)
Chemiluminescent Method	(1)
Electrochemical Cell	(2)
Mass Spectrometer	(1)
Faristor	(1)
Nitrogen Dioxide	
NDUV	(4)
NDIR (by conversion to NO)	(1)

TABLE 45 (CONTINUED)

EXHAUST GAS ANALYSIS METHODS IN USE AT 17 ORGANIZATIONS

Analysis Method	Number Using Method
Nitrogen Oxides	
Electrochemical Cell	(2)
Chemiluminescent Method	(2)
NDUV (assuming exhaust is NO and NO_2; NO previously determined)	(2)
PDS	(2)
Faristor	(1)
Particulates	
Mass Determination	(4)
Mass Determination and Sizing by Electron Microscope	(2) (2)
Mass Determination and Wet Chemical Analysis	(2)
Smoke	
Per SAE, ARP 1179	(10)
Other	(3)
Sulfur Dioxide	
Calculated	(6)
Faristor	(2)
Aldehydes	
MBTH	(6)

FIGURES

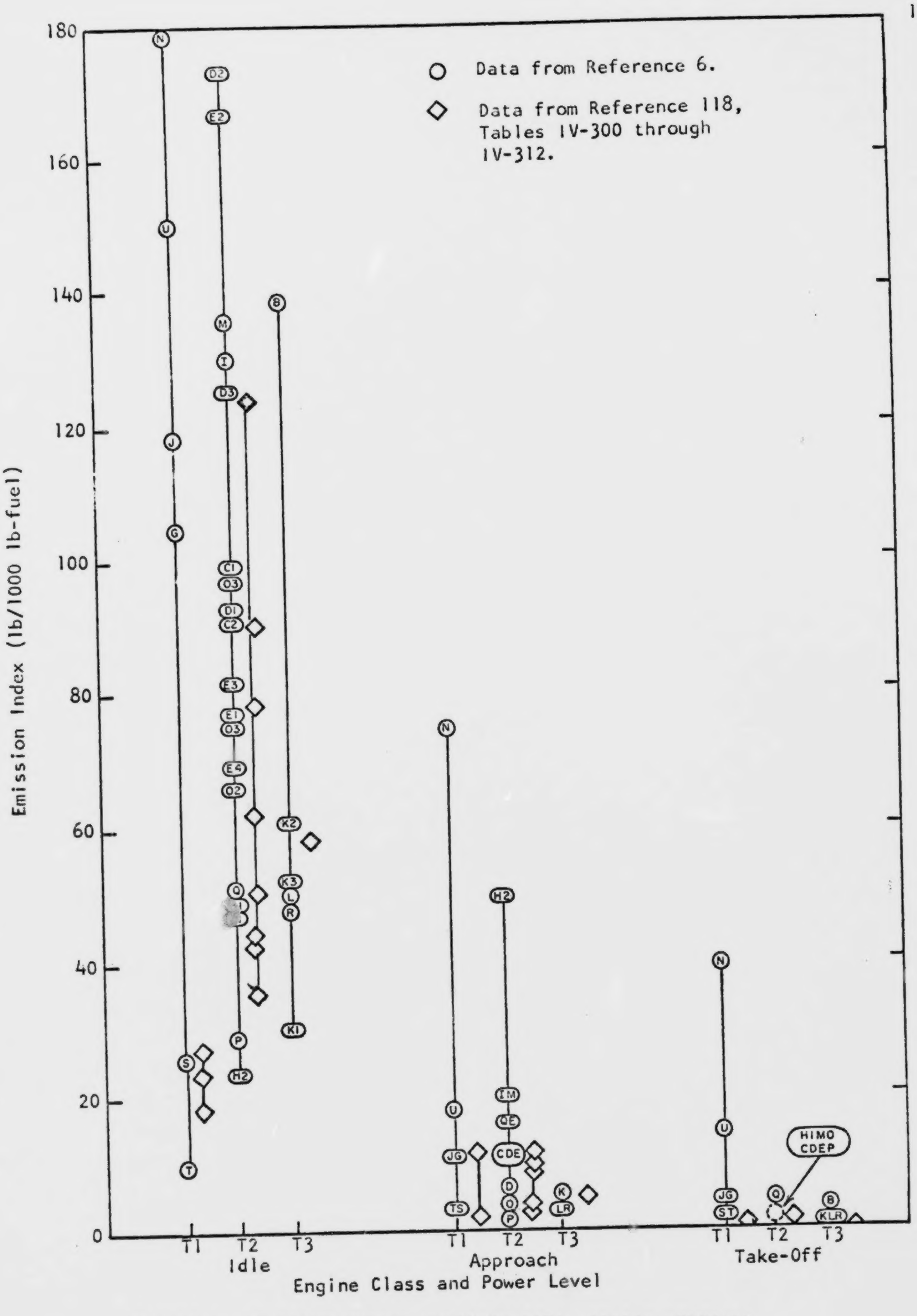


FIGURE 1 - TURBINE ENGINE EMISSION DATA, CARBON MONOXIDE

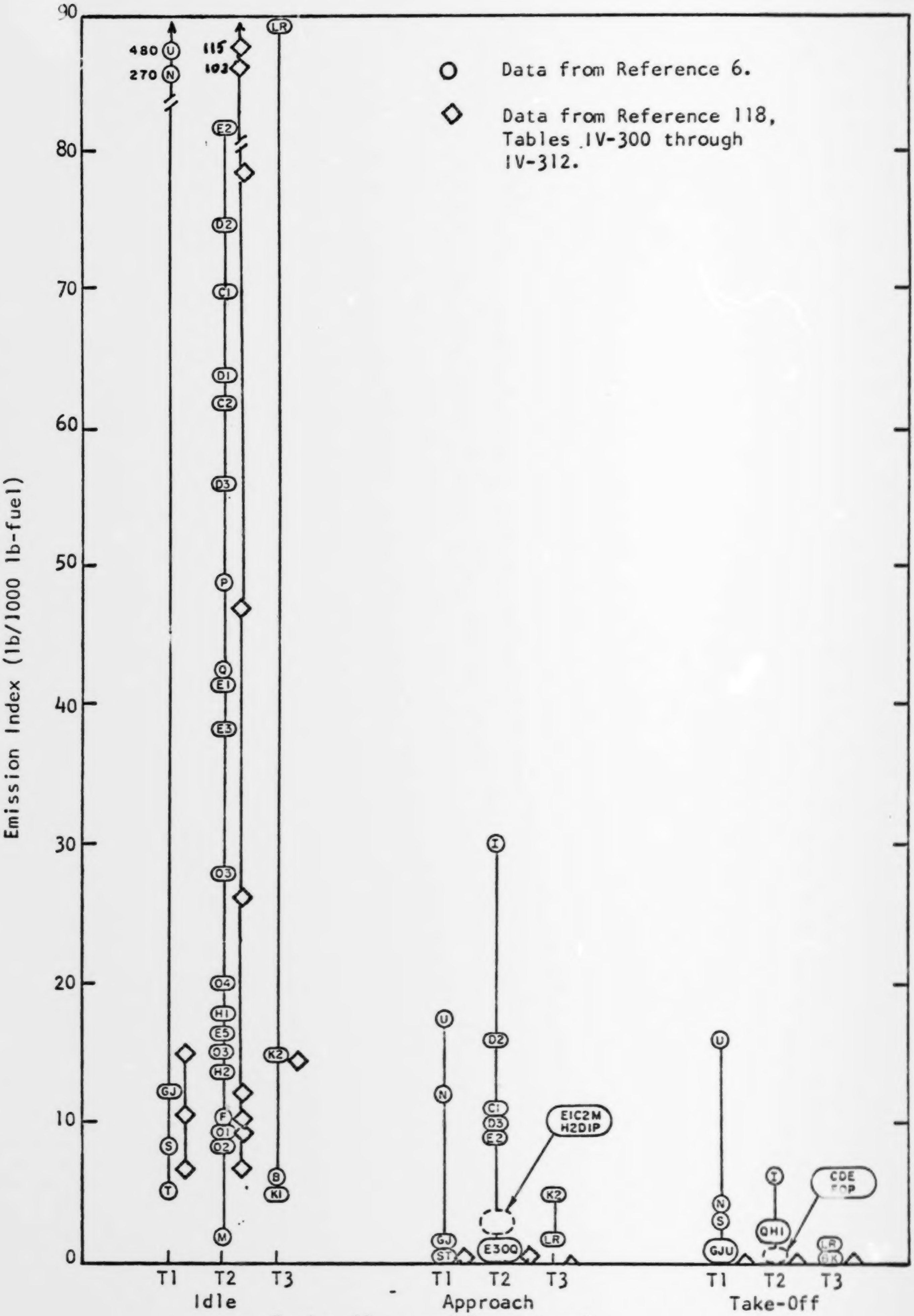


FIGURE 2 - TURBINE ENGINE EMISSION DATA, TOTAL HYDROCARBONS (AS CH4)

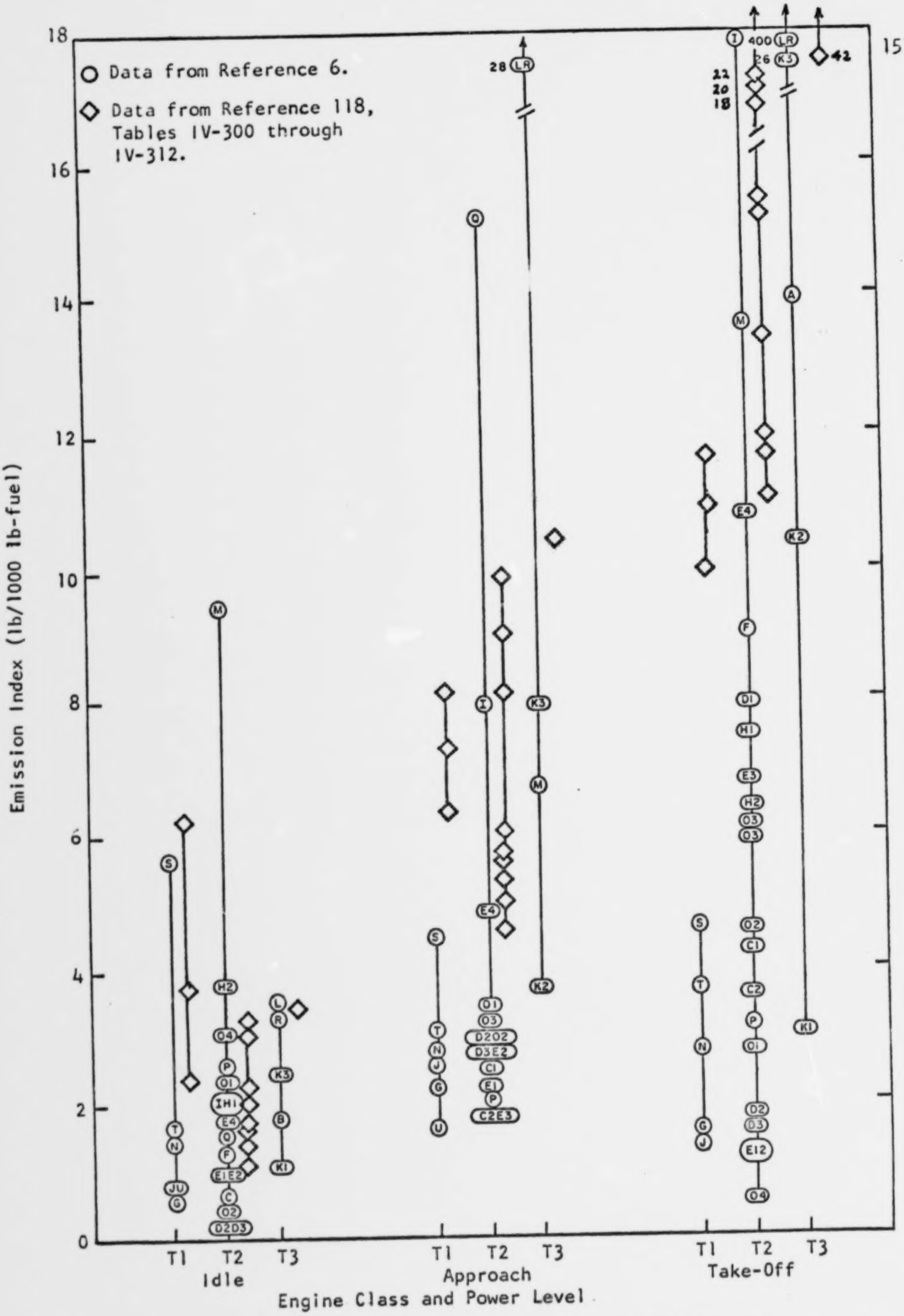


FIGURE 3 - TURBINE ENGINE EMISSION DATA, NITROGEN OXIDES (AS NO_2)

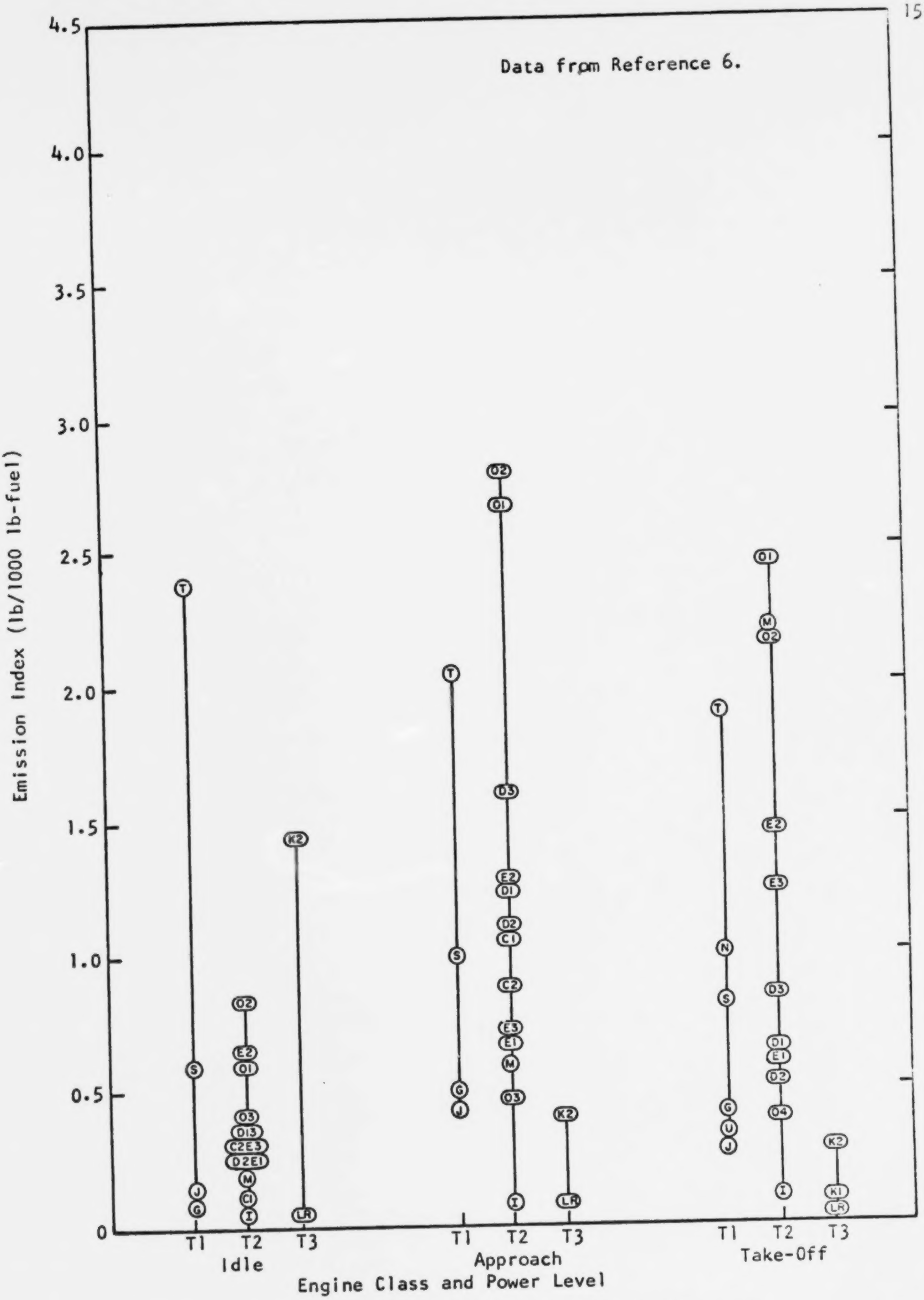


FIGURE 4 - TURBINE ENGINE EMISSION DATA, DRY PARTICULATES

Assumptions

Turbine Engines

1. TBO = Time Between Overhauls = 5000 hrs = 2½ years
2. Engine Life = 10 years

Piston Engines

1. TBO = 1500 hrs = 5 years
2. Engine Life = 10 years

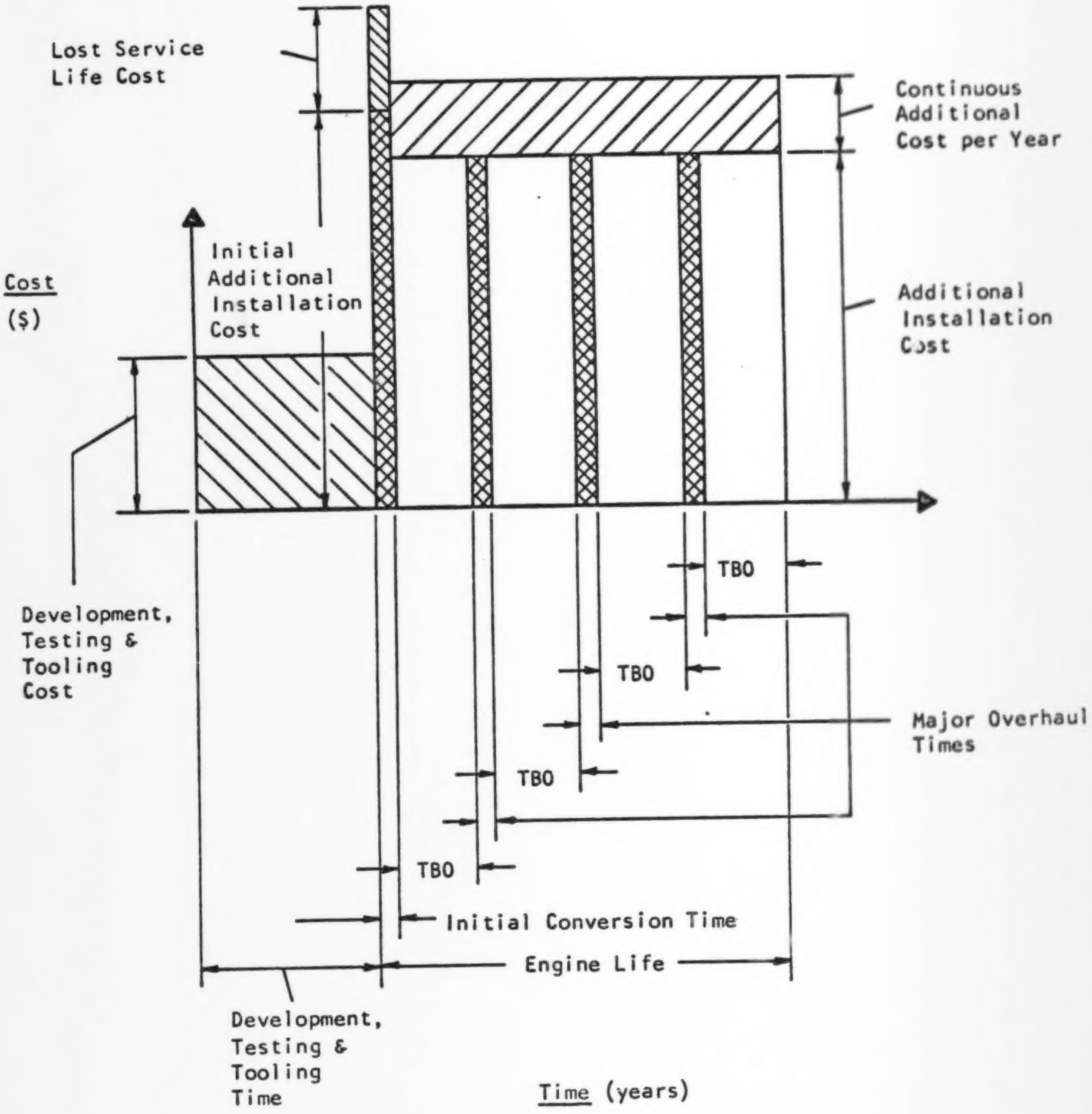
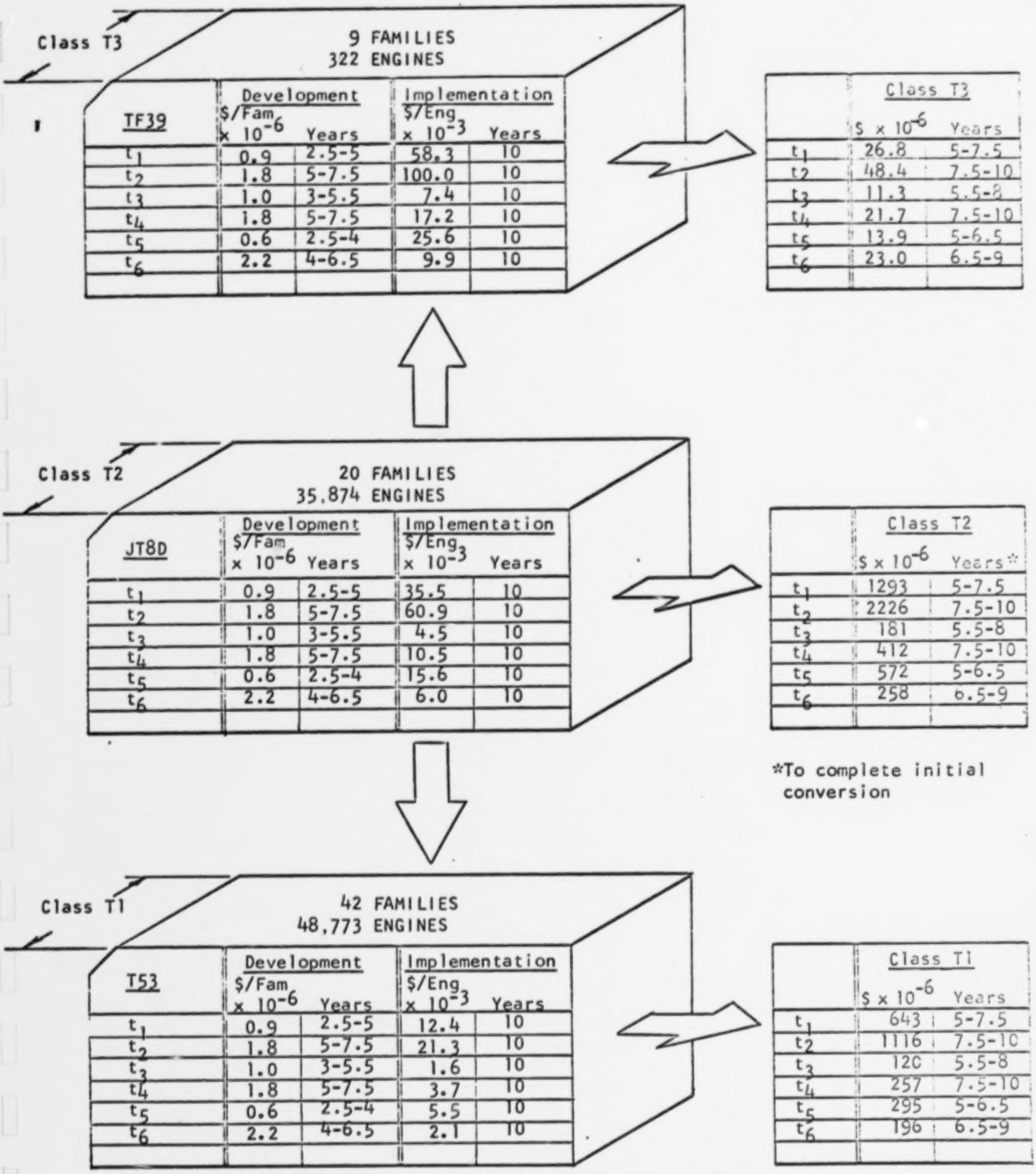

Lost Service Life Cost
Continuous Additional Cost per Year
Initial Additional Installation Cost
Cost ($)
Additional Installation Cost
Development, Testing & Tooling Cost
TBO
TBO
Major Overhaul Times
TBO
TBO
Initial Conversion Time
Engine Life
Development, Testing & Tooling Time
Time (years)

FIGURE 5 - EMISSION CONTROL COST/TIME MODEL FOR TYPICAL AIRCRAFT ENGINE FAMILY CURRENTLY IN-SERVICE


Class T3
9 FAMILIES
322 ENGINES
Class T2
20 FAMILIES
35,874 ENGINES
Class T1
42 FAMILIES
48,773 ENGINES

TF39	Development		Implementation	
	$/Fam × 10^{-6}	Years	$/Eng × 10^{-3}	Years
t_1	0.9	2.5-5	58.3	10
t_2	1.8	5-7.5	100.0	10
t_3	1.0	3-5.5	7.4	10
t_4	1.8	5-7.5	17.2	10
t_5	0.6	2.5-4	25.6	10
t_6	2.2	4-6.5	9.9	10

	Class T3	
	$ × 10^{-6}	Years
t_1	26.8	5-7.5
t_2	48.4	7.5-10
t_3	11.3	5.5-8
t_4	21.7	7.5-10
t_5	13.9	5-6.5
t_6	23.0	6.5-9

JT8D	Development		Implementation	
	$/Fam × 10^{-6}	Years	$/Eng × 10^{-3}	Years
t_1	0.9	2.5-5	35.5	10
t_2	1.8	5-7.5	60.9	10
t_3	1.0	3-5.5	4.5	10
t_4	1.8	5-7.5	10.5	10
t_5	0.6	2.5-4	15.6	10
t_6	2.2	4-6.5	6.0	10

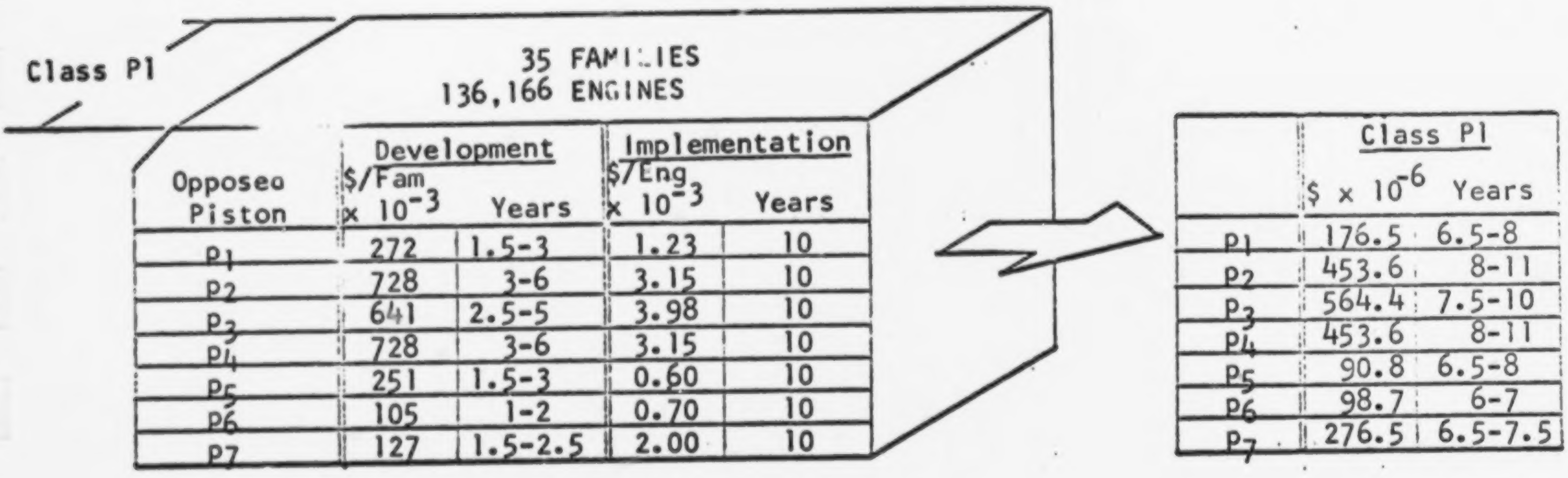
	Class T2	
	$ × 10^{-6}	Years*
t_1	1293	5-7.5
t_2	2226	7.5-10
t_3	181	5.5-8
t_4	412	7.5-10
t_5	572	5-6.5
t_6	258	6.5-9

*To complete initial conversion

T53	Development		Implementation	
	$/Fam × 10^{-6}	Years	$/Eng × 10^{-3}	Years
t_1	0.9	2.5-5	12.4	10
t_2	1.8	5-7.5	21.3	10
t_3	1.0	3-5.5	1.6	10
t_4	1.8	5-7.5	3.7	10
t_5	0.6	2.5-4	5.5	10
t_6	2.2	4-6.5	2.1	10

	Class T1	
	$ × 10^{-6}	Years
t_1	643	5-7.5
t_2	1116	7.5-10
t_3	120	5.5-8
t_4	257	7.5-10
t_5	295	5-6.5
t_6	196	6.5-9

FIGURE 6 - SUMMARY OF TOTAL TURBINE ENGINE POPULATION COST/TIME ANALYSIS PROCEDURE



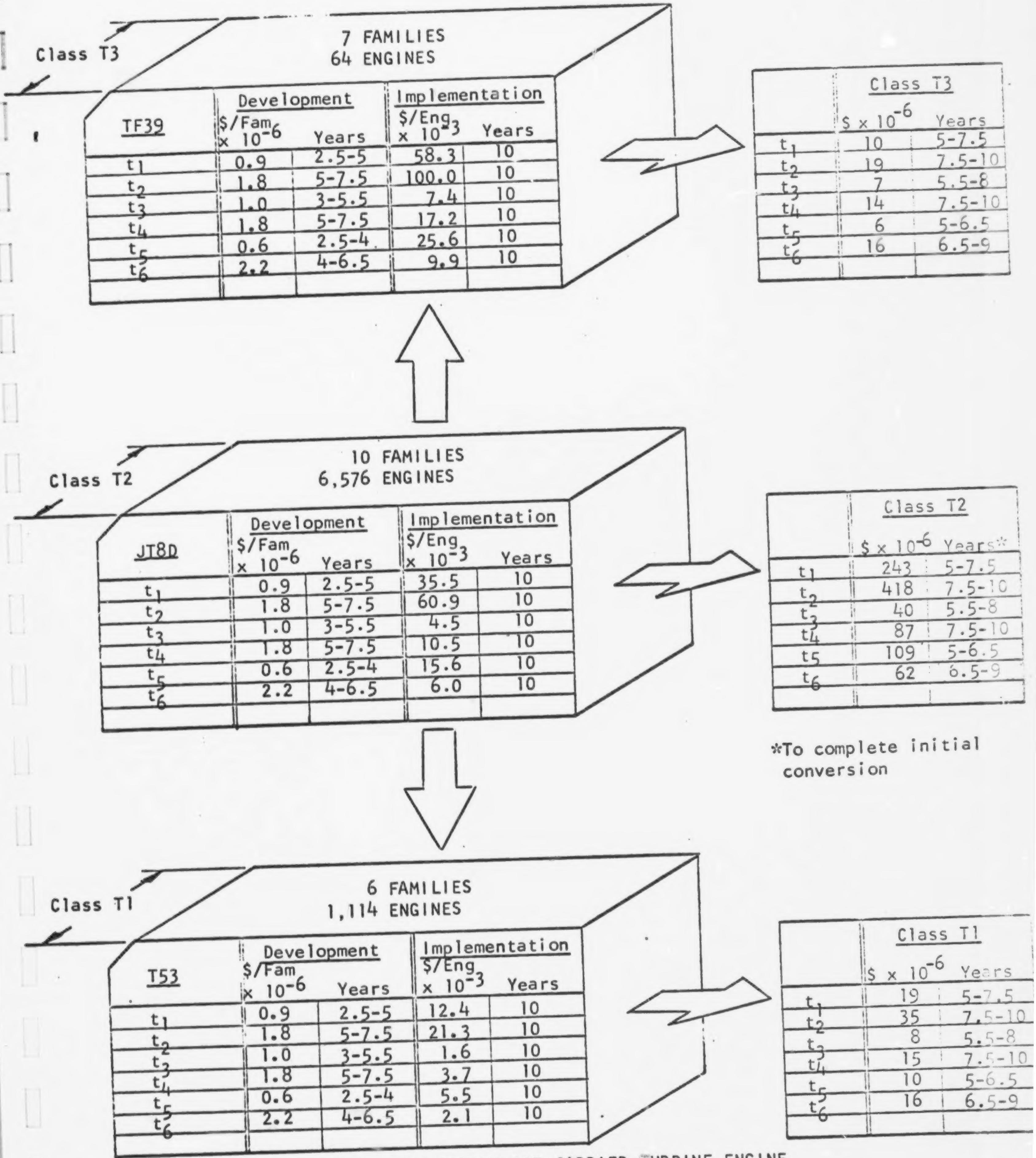
Class P1

35 FAMILIES
136,166 ENGINES

Opposed Piston	Development $/Fam $\times 10^{-3}$	Development Years	Implementation $/Eng $\times 10^{-3}$	Implementation Years
P_1	272	1.5-3	1.23	10
P_2	728	3-6	3.15	10
P_3	641	2.5-5	3.98	10
P_4	728	3-6	3.15	10
P_5	251	1.5-3	0.60	10
P_6	105	1-2	0.70	10
P_7	127	1.5-2.5	2.00	10

	Class P1 $\$ \times 10^{-6}$	Class P1 Years
P_1	176.5	6.5-8
P_2	453.6	8-11
P_3	564.4	7.5-10
P_4	453.6	8-11
P_5	90.8	6.5-8
P_6	98.7	6-7
P_7	276.5	6.5-7.5

FIGURE 6A - SUMMARY OF TOTAL PISTON ENGINE POPULATION COST/TIME ANALYSIS PROCEDURE



Class T3

7 FAMILIES
64 ENGINES

TF39	Development		Implementation	
	$/Fam $\times 10^{-6}$	Years	$/Eng $\times 10^{-3}$	Years
t_1	0.9	2.5-5	58.3	10
t_2	1.8	5-7.5	100.0	10
t_3	1.0	3-5.5	7.4	10
t_4	1.8	5-7.5	17.2	10
t_5	0.6	2.5-4	25.6	10
t_6	2.2	4-6.5	9.9	10

	Class T3	
	$\$ \times 10^{-6}$	Years
t_1	10	5-7.5
t_2	19	7.5-10
t_3	7	5.5-8
t_4	14	7.5-10
t_5	6	5-6.5
t_6	16	6.5-9

Class T2

10 FAMILIES
6,576 ENGINES

JT8D	Development		Implementation	
	$/Fam $\times 10^{-6}$	Years	$/Eng $\times 10^{-3}$	Years
t_1	0.9	2.5-5	35.5	10
t_2	1.8	5-7.5	60.9	10
t_3	1.0	3-5.5	4.5	10
t_4	1.8	5-7.5	10.5	10
t_5	0.6	2.5-4	15.6	10
t_6	2.2	4-6.5	6.0	10

	Class T2	
	$\$ \times 10^{-6}$	Years*
t_1	243	5-7.5
t_2	418	7.5-10
t_3	40	5.5-8
t_4	87	7.5-10
t_5	109	5-6.5
t_6	62	6.5-9

*To complete initial conversion

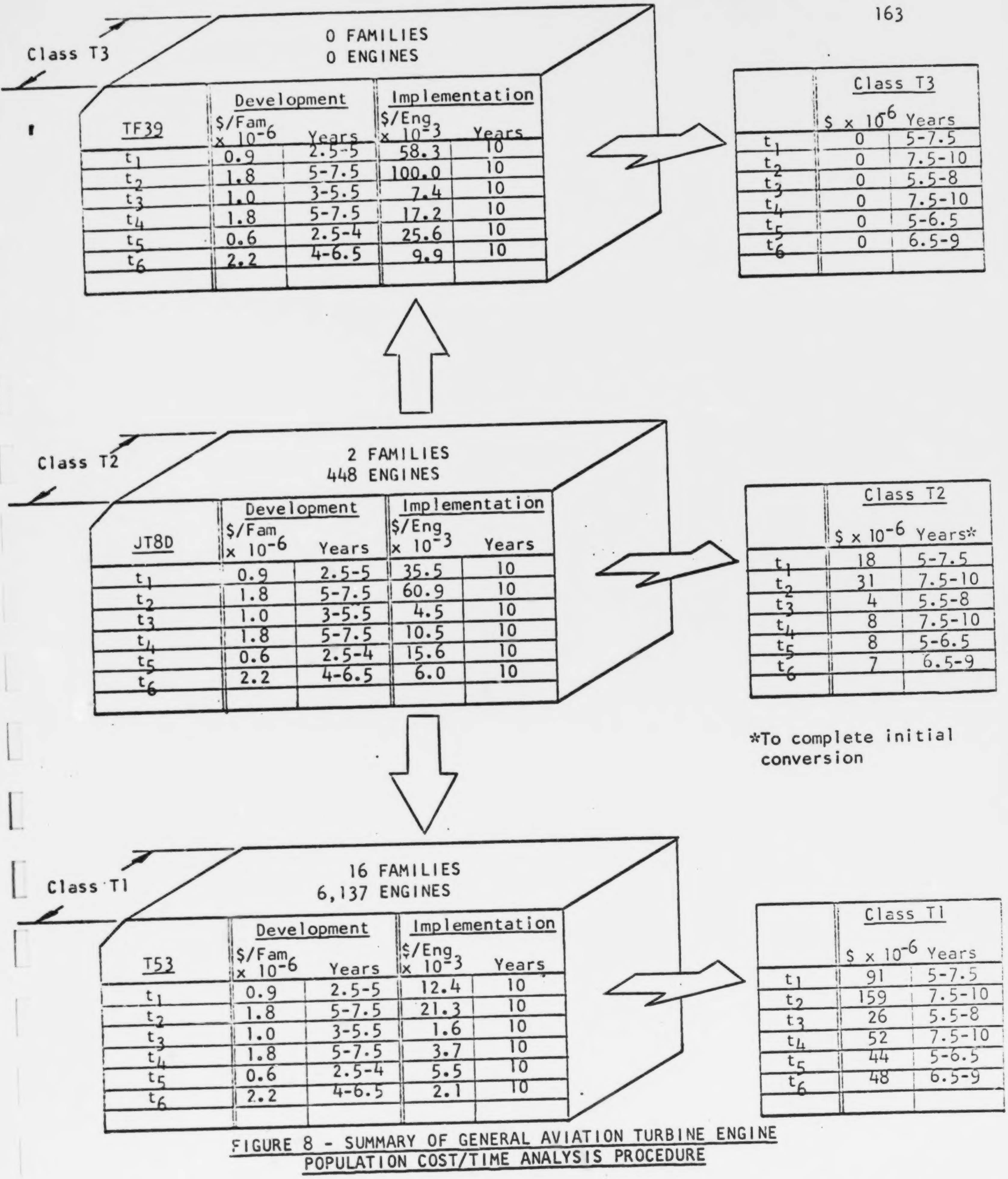
Class T1

6 FAMILIES
1,114 ENGINES

T53	Development		Implementation	
	$/Fam $\times 10^{-6}$	Years	$/Eng $\times 10^{-3}$	Years
t_1	0.9	2.5-5	12.4	10
t_2	1.8	5-7.5	21.3	10
t_3	1.0	3-5.5	1.6	10
t_4	1.8	5-7.5	3.7	10
t_5	0.6	2.5-4	5.5	10
t_6	2.2	4-6.5	2.1	10

	Class T1	
	$\$ \times 10^{-6}$	Years
t_1	19	5-7.5
t_2	35	7.5-10
t_3	8	5.5-8
t_4	15	7.5-10
t_5	10	5-6.5
t_6	16	6.5-9

FIGURE 7 - SUMMARY OF AIR CARRIER TURBINE ENGINE POPULATION COST/TIME ANALYSIS PROCEDURE



TF39	Development $/Fam x 10^{-6}	Development Years	Implementation $/Eng x 10^{-3}	Implementation Years
t_1	0.9	2.5-5	58.3	10
t_2	1.8	5-7.5	100.0	10
t_3	1.0	3-5.5	7.4	10
t_4	1.8	5-7.5	17.2	10
t_5	0.6	2.5-4	25.6	10
t_6	2.2	4-6.5	9.9	10

	Class T3 $ x 10^{-6}	Class T3 Years
t_1	0	5-7.5
t_2	0	7.5-10
t_3	0	5.5-8
t_4	0	7.5-10
t_5	0	5-6.5
t_6	0	6.5-9

JT8D	Development $/Fam x 10^{-6}	Development Years	Implementation $/Eng x 10^{-3}	Implementation Years
t_1	0.9	2.5-5	35.5	10
t_2	1.8	5-7.5	60.9	10
t_3	1.0	3-5.5	4.5	10
t_4	1.8	5-7.5	10.5	10
t_5	0.6	2.5-4	15.6	10
t_6	2.2	4-6.5	6.0	10

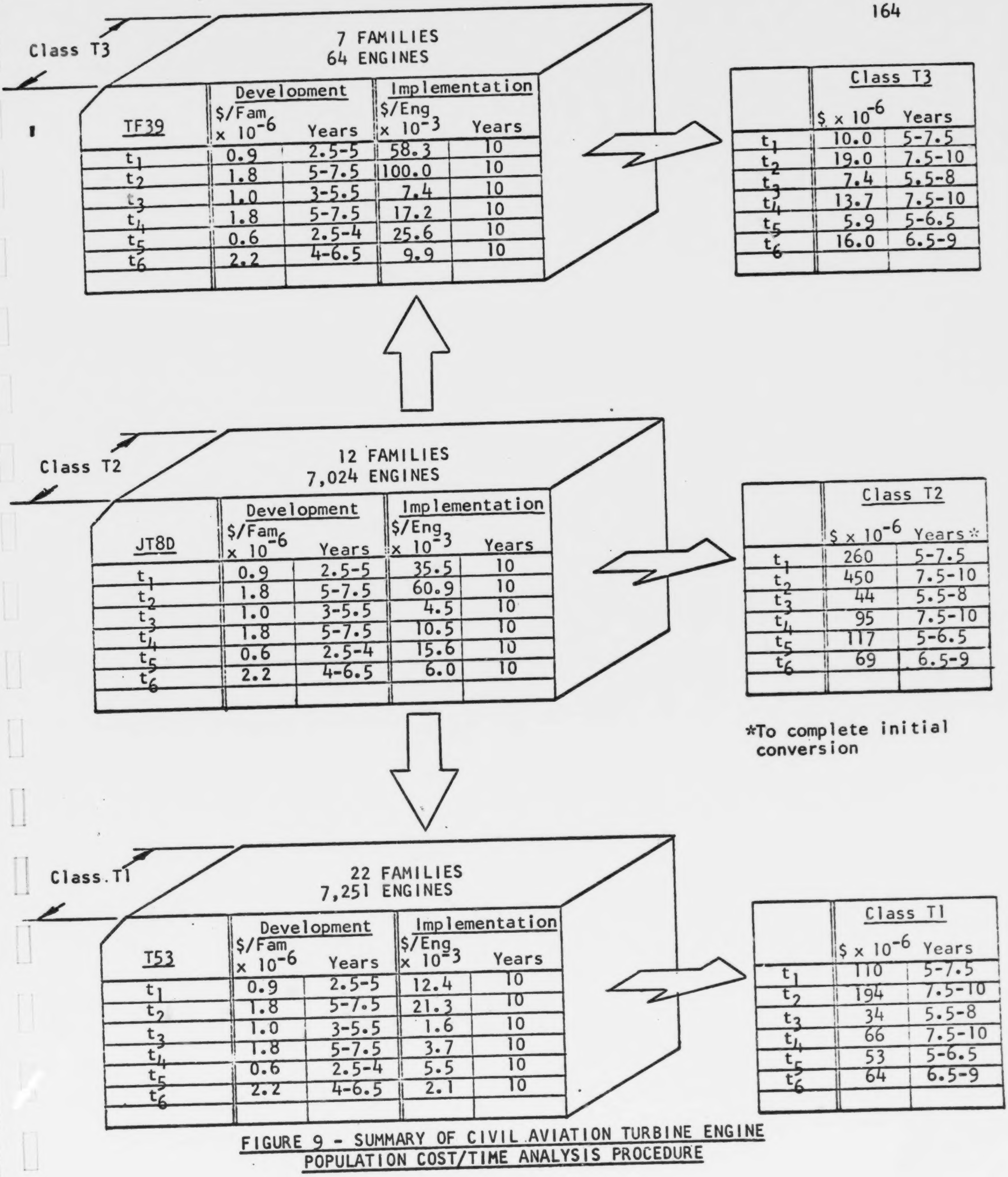
	Class T2 $ x 10^{-6}	Class T2 Years*
t_1	18	5-7.5
t_2	31	7.5-10
t_3	4	5.5-8
t_4	8	7.5-10
t_5	8	5-6.5
t_6	7	6.5-9

*To complete initial conversion

T53	Development $/Fam x 10^{-6}	Development Years	Implementation $/Eng x 10^{-3}	Implementation Years
t_1	0.9	2.5-5	12.4	10
t_2	1.8	5-7.5	21.3	10
t_3	1.0	3-5.5	1.6	10
t_4	1.8	5-7.5	3.7	10
t_5	0.6	2.5-4	5.5	10
t_6	2.2	4-6.5	2.1	10

	Class T1 $ x 10^{-6}	Class T1 Years
t_1	91	5-7.5
t_2	159	7.5-10
t_3	26	5.5-8
t_4	52	7.5-10
t_5	44	5-6.5
t_6	48	6.5-9

FIGURE 8 - SUMMARY OF GENERAL AVIATION TURBINE ENGINE POPULATION COST/TIME ANALYSIS PROCEDURE



Class T3

7 FAMILIES
64 ENGINES

TF39	Development $/Fam × 10^{-6}	Development Years	Implementation $/Eng × 10^{-3}	Implementation Years
t_1	0.9	2.5-5	58.3	10
t_2	1.8	5-7.5	100.0	10
t_3	1.0	3-5.5	7.4	10
t_4	1.8	5-7.5	17.2	10
t_5	0.6	2.5-4	25.6	10
t_6	2.2	4-6.5	9.9	10

	Class T3 $ × 10^{-6}	Class T3 Years
t_1	10.0	5-7.5
t_2	19.0	7.5-10
t_3	7.4	5.5-8
t_4	13.7	7.5-10
t_5	5.9	5-6.5
t_6	16.0	6.5-9

Class T2

12 FAMILIES
7,024 ENGINES

JT8D	Development $/Fam × 10^{-6}	Development Years	Implementation $/Eng × 10^{-3}	Implementation Years
t_1	0.9	2.5-5	35.5	10
t_2	1.8	5-7.5	60.9	10
t_3	1.0	3-5.5	4.5	10
t_4	1.8	5-7.5	10.5	10
t_5	0.6	2.5-4	15.6	10
t_6	2.2	4-6.5	6.0	10

	Class T2 $ × 10^{-6}	Class T2 Years*
t_1	260	5-7.5
t_2	450	7.5-10
t_3	44	5.5-8
t_4	95	7.5-10
t_5	117	5-6.5
t_6	69	6.5-9

*To complete initial conversion

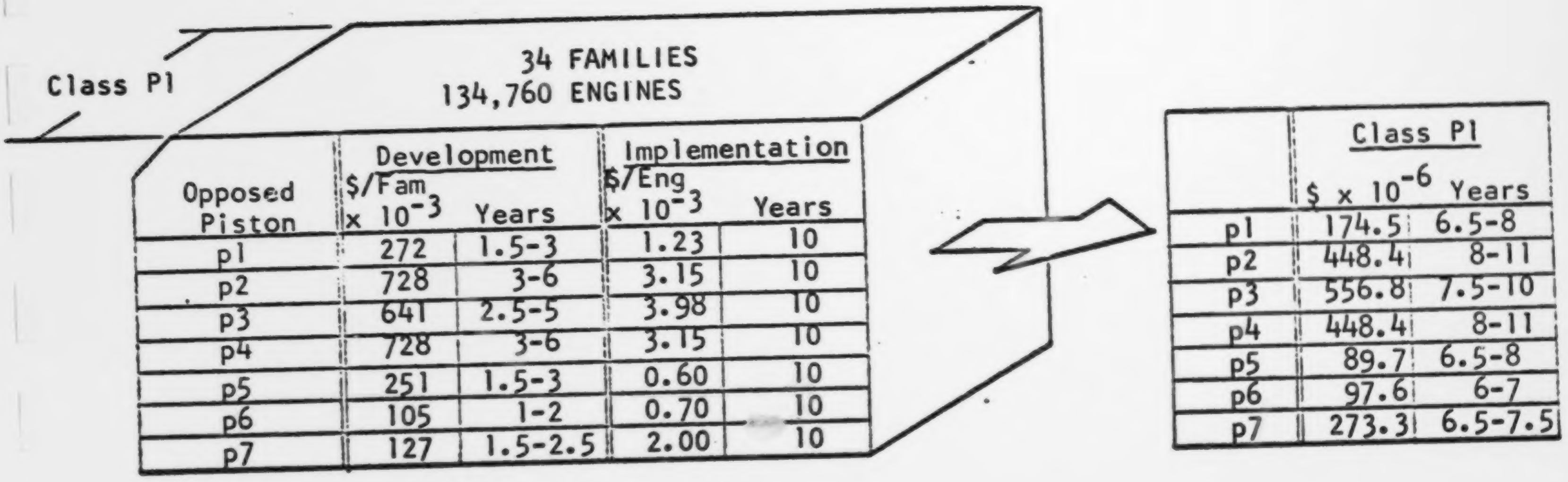
Class T1

22 FAMILIES
7,251 ENGINES

T53	Development $/Fam × 10^{-6}	Development Years	Implementation $/Eng × 10^{-3}	Implementation Years
t_1	0.9	2.5-5	12.4	10
t_2	1.8	5-7.5	21.3	10
t_3	1.0	3-5.5	1.6	10
t_4	1.8	5-7.5	3.7	10
t_5	0.6	2.5-4	5.5	10
t_6	2.2	4-6.5	2.1	10

	Class T1 $ × 10^{-6}	Class T1 Years
t_1	110	5-7.5
t_2	194	7.5-10
t_3	34	5.5-8
t_4	66	7.5-10
t_5	53	5-6.5
t_6	64	6.5-9

FIGURE 9 - SUMMARY OF CIVIL AVIATION TURBINE ENGINE POPULATION COST/TIME ANALYSIS PROCEDURE

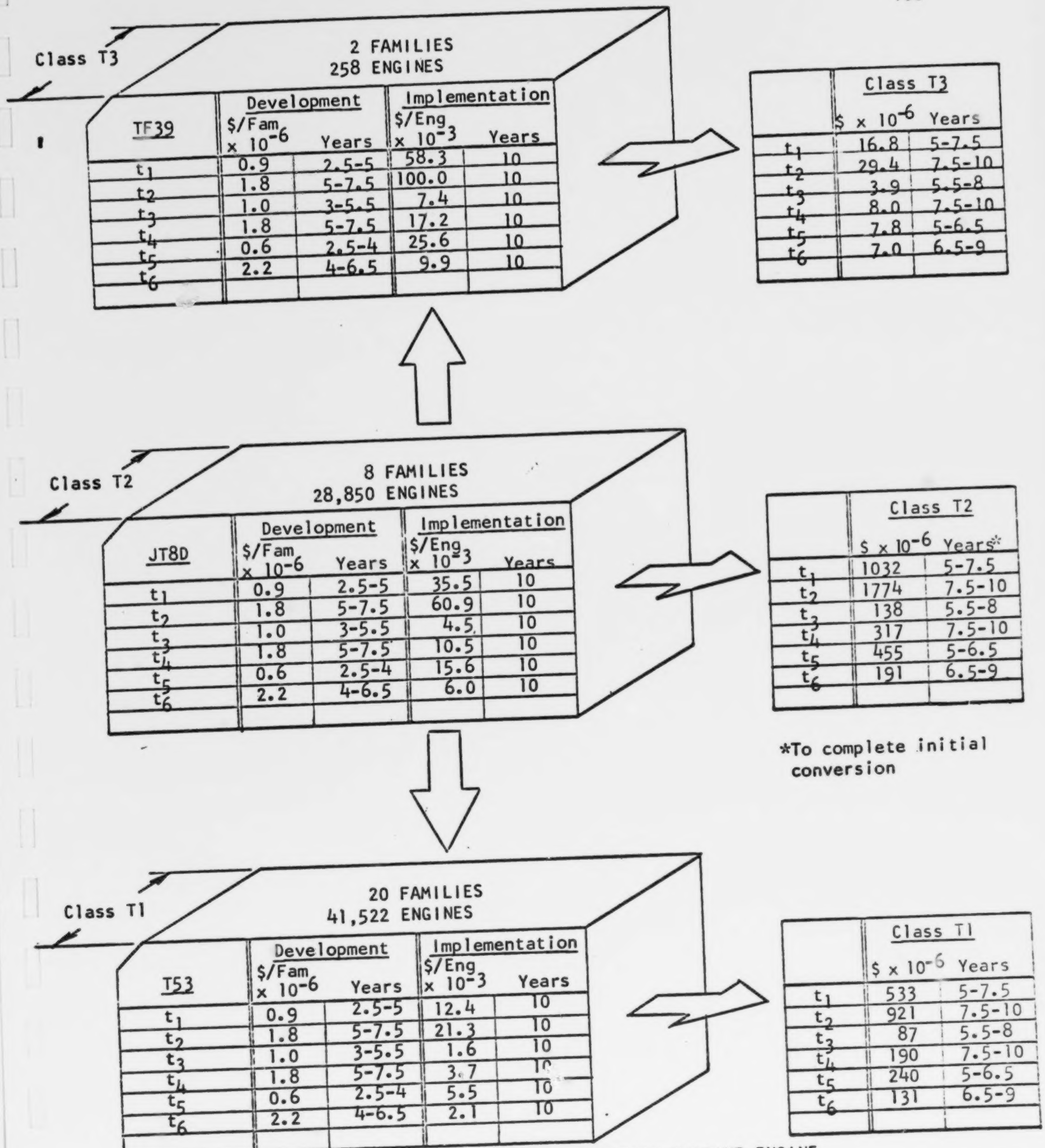


Opposed Piston	Development $/Fam x 10^{-3}	Development Years	Implementation $/Eng x 10^{-3}	Implementation Years
p1	272	1.5-3	1.23	10
p2	728	3-6	3.15	10
p3	641	2.5-5	3.98	10
p4	728	3-6	3.15	10
p5	251	1.5-3	0.60	10
p6	105	1-2	0.70	10
p7	127	1.5-2.5	2.00	10

	Class P1 $ x 10^{-6}	Class P1 Years
p1	174.5	6.5-8
p2	448.4	8-11
p3	556.8	7.5-10
p4	448.4	8-11
p5	89.7	6.5-8
p6	97.6	6-7
p7	273.3	6.5-7.5

NOTE: Air carrier piston engine population assumed negligible.
Therefore, air carrier population = civil aviation population.

FIGURE 9A - SUMMARY OF CIVIL AVIATION PISTON ENGINE POPULATION COST/TIME ANALYSIS PROCEDURE


Class T3
2 FAMILIES
258 ENGINES
Class T2
8 FAMILIES
28,850 ENGINES
Class T1
20 FAMILIES
41,522 ENGINES

TF39	Development		Implementation	
	$/Fam $\times 10^{-6}$	Years	$/Eng $\times 10^{-3}$	Years
t_1	0.9	2.5-5	58.3	10
t_2	1.8	5-7.5	100.0	10
t_3	1.0	3-5.5	7.4	10
t_4	1.8	5-7.5	17.2	10
t_5	0.6	2.5-4	25.6	10
t_6	2.2	4-6.5	9.9	10

	Class T3	
	$ $\times 10^{-6}$	Years
t_1	16.8	5-7.5
t_2	29.4	7.5-10
t_3	3.9	5.5-8
t_4	8.0	7.5-10
t_5	7.8	5-6.5
t_6	7.0	6.5-9

JT8D	Development		Implementation	
	$/Fam $\times 10^{-6}$	Years	$/Eng $\times 10^{-3}$	Years
t_1	0.9	2.5-5	35.5	10
t_2	1.8	5-7.5	60.9	10
t_3	1.0	3-5.5	4.5	10
t_4	1.8	5-7.5	10.5	10
t_5	0.6	2.5-4	15.6	10
t_6	2.2	4-6.5	6.0	10

	Class T2	
	$ $\times 10^{-6}$	Years*
t_1	1032	5-7.5
t_2	1774	7.5-10
t_3	138	5.5-8
t_4	317	7.5-10
t_5	455	5-6.5
t_6	191	6.5-9

*To complete initial conversion

T53	Development		Implementation	
	$/Fam $\times 10^{-6}$	Years	$/Eng $\times 10^{-3}$	Years
t_1	0.9	2.5-5	12.4	10
t_2	1.8	5-7.5	21.3	10
t_3	1.0	3-5.5	1.6	10
t_4	1.8	5-7.5	3.7	10
t_5	0.6	2.5-4	5.5	10
t_6	2.2	4-6.5	2.1	10

	Class T1	
	$ $\times 10^{-6}$	Years
t_1	533	5-7.5
t_2	921	7.5-10
t_3	87	5.5-8
t_4	190	7.5-10
t_5	240	5-6.5
t_6	131	6.5-9

FIGURE 10 - SUMMARY OF MILITARY AVIATION TURBINE ENGINE POPULATION COST/TIME ANALYSIS PROCEDURE

lass P1

1 FAMILIES
1,406 ENGINES

Opposed Piston	Development		Implementation	
	$/Fam $\times 10^{-3}$	Years	$/Eng $\times 10^{-3}$	Years
p1	272	1.5-3	1.23	10
p2	728	3-6	3.15	10
p3	641	2.5-5	3.98	10
p4	728	3-6	3.15	10
p5	251	1.5-3	0.60	10
p6	105	1-2	0.70	10
p7	127	1.5-2.5	2.00	10

	Class P1	
	$ $\times 10^{-6}$	Years
p1	2.0	6.3-8
p2	5.2	8-11
p3	6.3	7.5-11
p4	5.2	8-11
p5	1.1	6.5-8
p6	1.1	6-7
p7	3.0	6.5-7.5

FIGURE 10A - SUMMARY OF MILITARY AVIATION PISTON ENGINE POPULATION COST/TIME ANALYSIS PROCEDURE

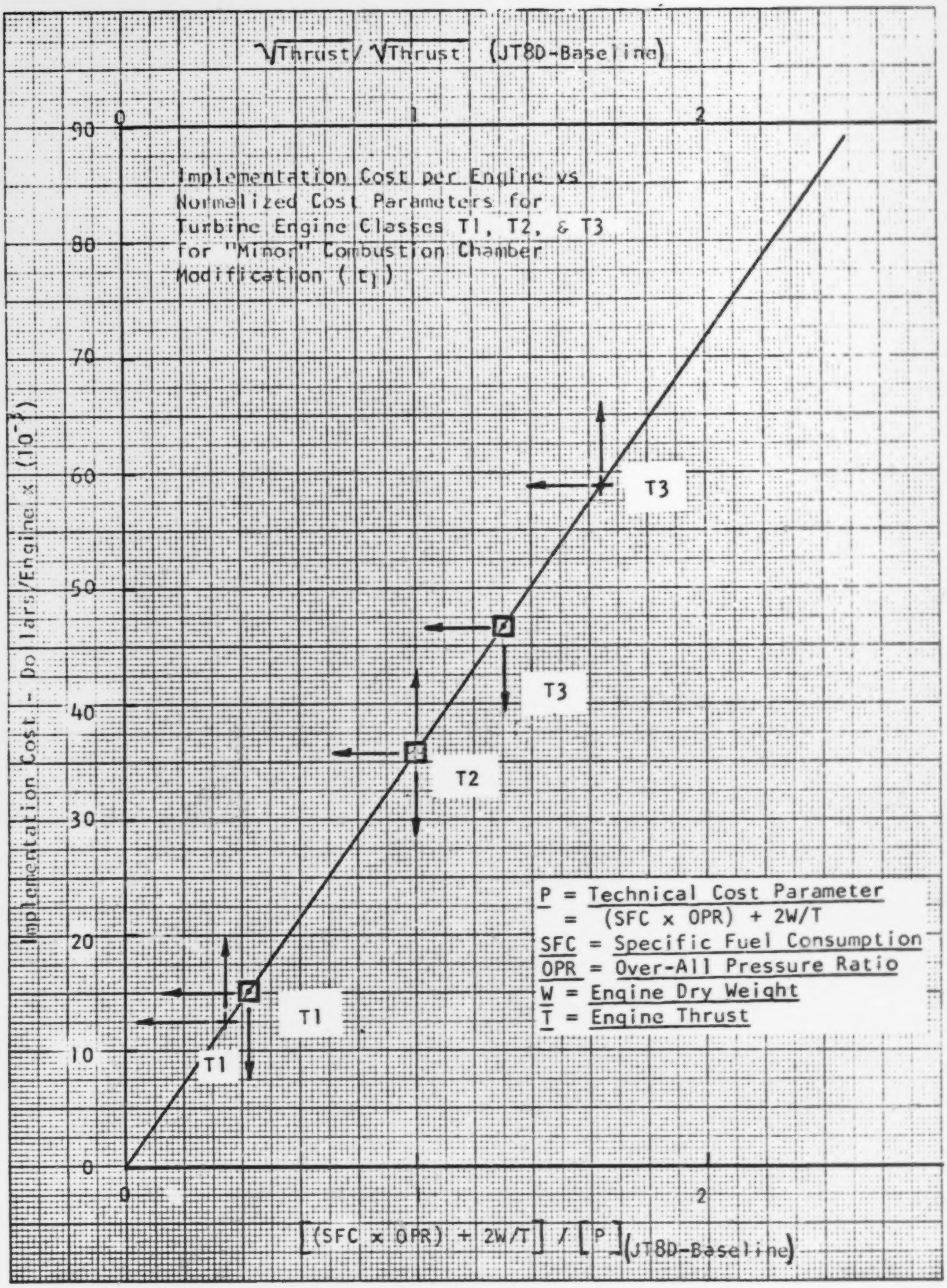


FIGURE 11 - IMPLEMENTATION COST PER ENGINE VERSUS NORMALIZED COST PARAMETERS FOR TURBINE ENGINE

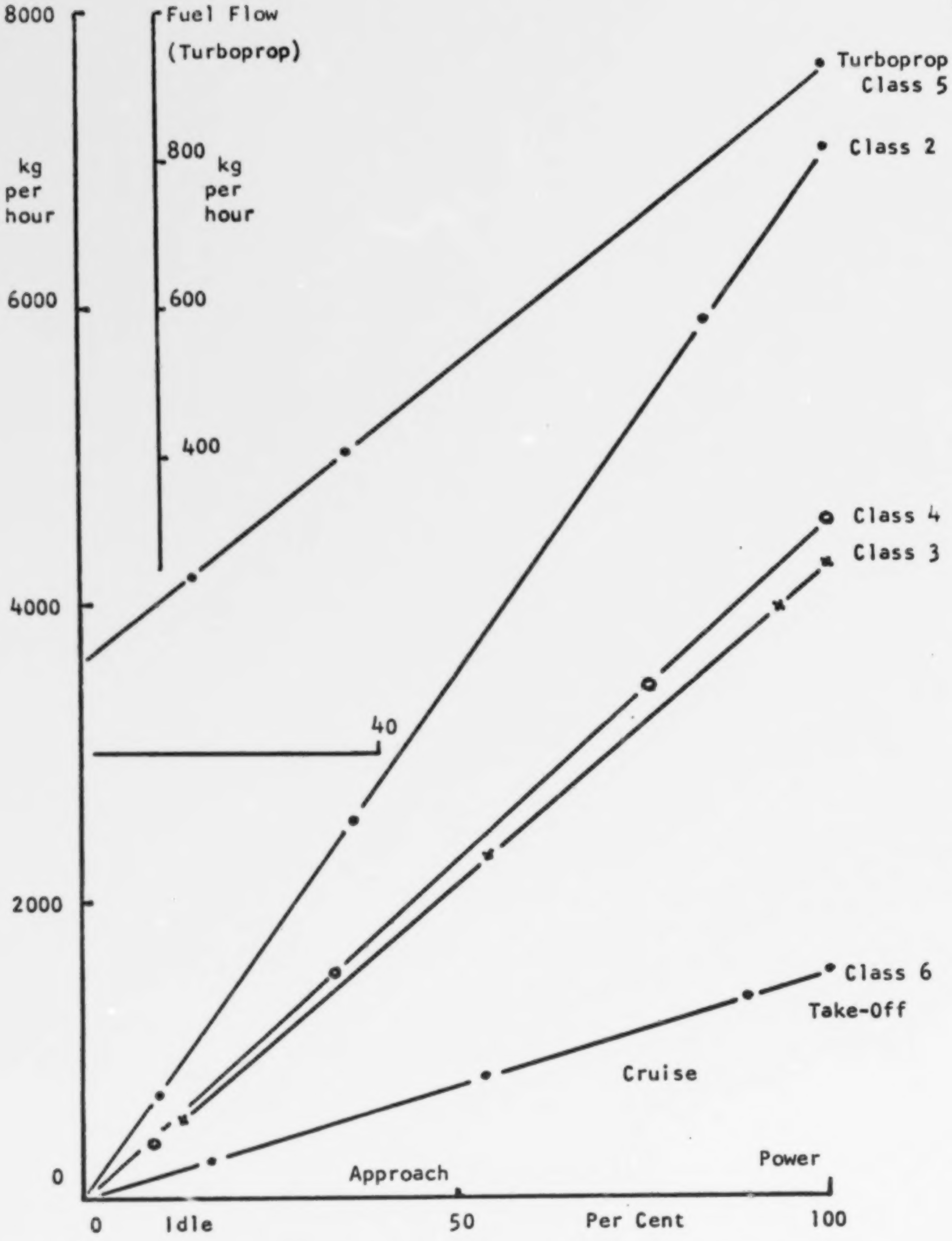


FIGURE 12 - FUEL FLOW PLOTTED AGAINST POWER FOR EACH AIRCRAFT CLASS

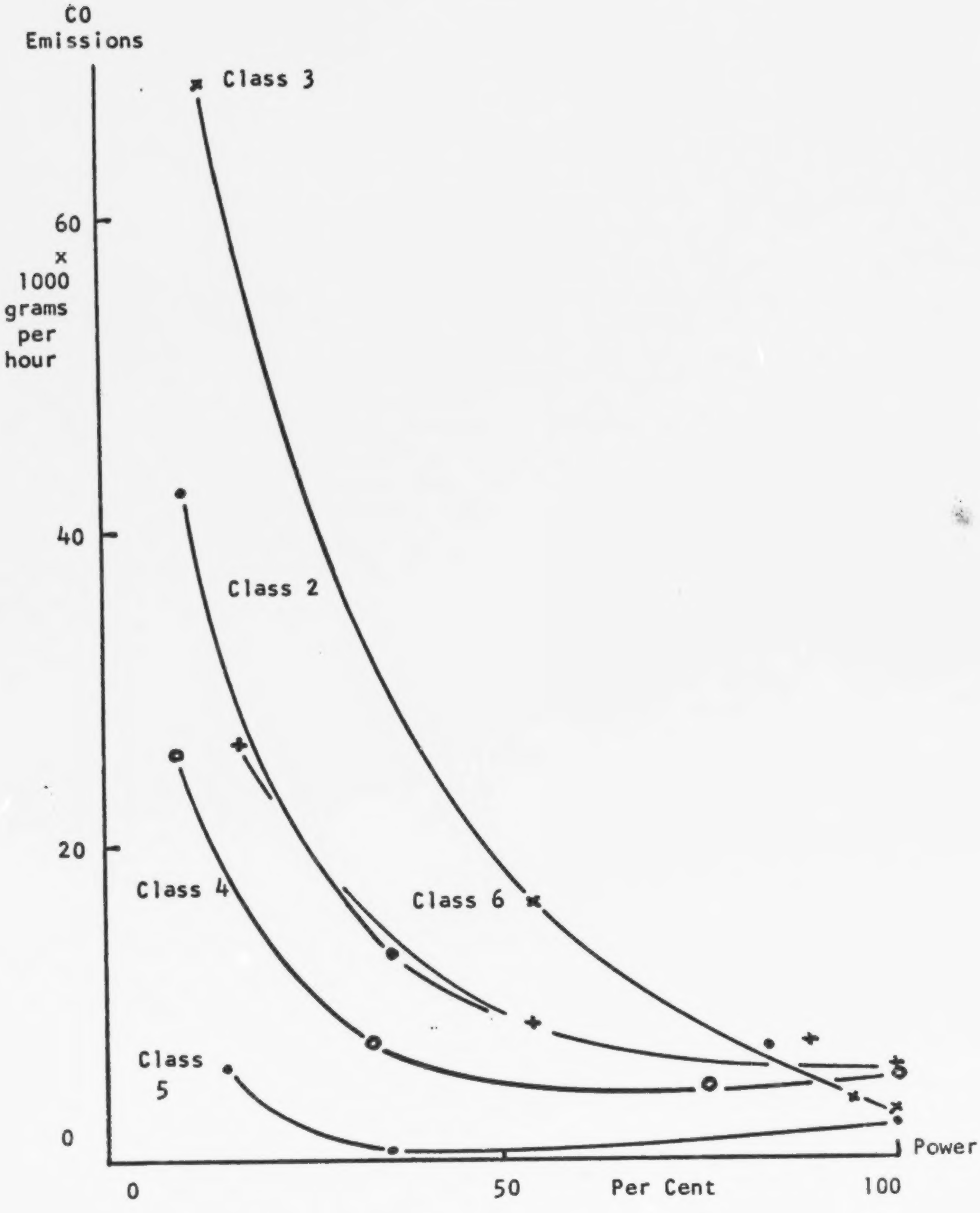


FIGURE 13 - CO EMISSION FACTORS PLOTTED AGAINST POWER FOR EACH AIRCRAFT CLASS

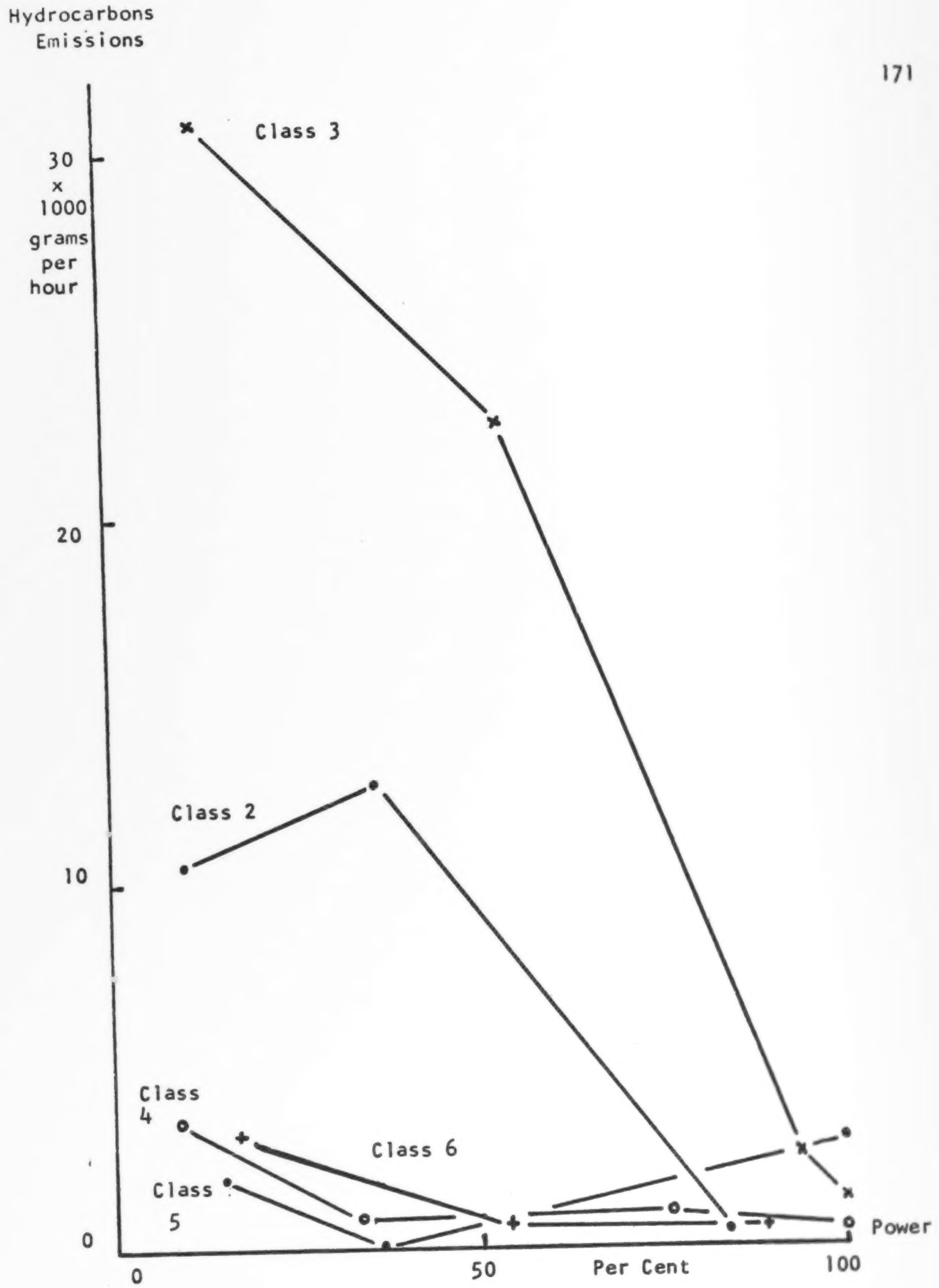


FIGURE 14 - HYDROCARBON EMISSION FACTORS PLOTTED AGAINST POWER FOR EACH AIRCRAFT CLASS

APPENDIX

INSTRUMENTATION

Introduction

The formation of the Committee on Aircraft Exhaust Emissions Measurement (E-31) by the Society of Automotive Engineers in 1968 represents a significant step towards the development of acceptable standards for characterization of aircraft engine exhausts. This committee has issued an Aerospace Recommended Practice (ARP-1179) on "Aircraft Gas Turbine Exhaust Smoke Measurement" (Ref 55) that has been widely accepted and adopted as a standard procedure by the aerospace community. Furthermore, the committee is completing work on a "Procedure for the Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines" (Ref 36) that specifies instrumentation, sampling, and test procedures that shall be used for measurement of carbon monoxide, carbon dioxide, nitric oxide, and total hydrocarbons in turbine exhausts. Before being discharged of its responsibilities, the committee will also examine procedures for odor characterization and measurement of particulates also in turbine engine exhausts. They will also reexamine the areas of emissions sampling procedures in the light of discoveries made subsequent to their recommendations on smoke measurement.

The forthcoming recommendations of the E-31 Committee on the characterization of aircraft gaseous emissions reflect a state-of-the-art analysis of existing measurement hardware. The committee's report does not, however, discuss alternative measurement techniques; it instead specifies standard measurement techniques and procedures that are to be followed in the aerospace community to insure the validity of data comparisons from one test program to another.

Consequently, to complement rather than duplicate the E-31 Committee's work, this discussion is directed towards various alternative instruments both available now, and under development, that could be used in an aircraft emissions measurement test program. This discussion will not include comparison of the cost and performance of the various brands of a specific type of instrument; the reader is referred to a recent study by Arthur D. Little, Inc. for such a comparison (Ref 60). Reference 61 also contains information on cost and detection principles for a number of commercially available continuous monitors.

In this Appendix, measurement techniques are discussed for the following pollutant classes:

Carbon Monoxide (CO)
Carbon Dioxide (CO_2)
Total Hydrocarbons
Nitric Oxide (NO)
Total Nitrogen Oxides (NOx)
Sulfur Dioxide (SO_2)
Aldehydes
Particulates
Smoke
Odor

The discussions include, where data are available, reference to performance characteristics, sensitivity, response time, costs, ease of use, auxiliary equipment requirements, and portability for each specific type of instrument. Problem areas indigenous to each instrument type are enumerated; instrumentation under development is identified; and, wherever applicable, the recommendations of the SAE E-31 Committee are cited.

Measurement Techniques

Carbon Monoxide

As discussed by Broderick et al (Ref 59), carbon monoxide emissions in aircraft engine exhausts are now measured by nondispersive infrared analyzers, by electrochemical analyzers, by mercury vapor analyzers, and by gas chromatographs. At the present time, the most widely accepted and used of these instruments is the NDIR analyzer. The instrument provides on-line analysis of emissions, has been successfully used in the field as a portable unit (Ref 3), can be easily operated by unskilled personnel, and carries the recommendation of the SAE E-31 Committee as an industry standard (Ref 36).

NDIR

In an infrared analyzer, radiant energy passes through a cell containing a reference gas and a cell containing the sample gas. In the sample cell, the radiation is absorbed by the components of interest in regions where that specie has absorption bands. The percentage absorption relates to the concentration of that specie. Interference from other components of the sample gas that absorb in neighboring bands is eliminated by optical filters or filter cells. In the reference cell, attenuation of the reference beam is negligible.

After passage through the cells, the radiant energy passes into a detector unit-- a closed container comprised of two compartments separated by a metal diaphragm. Both compartments are filled with the species of interest in the gaseous state. The incoming energy from the sample cell heats the gas in one compartment while the energy from the reference cell heats the gas in the other. The difference in incoming energy causes a pressure differential in the detector that leads to a deflection of the cell diaphragm.

Between the dual infrared energy sources is an optical chopper that chops the energy beams at a prescribed frequency. This chopping causes the diaphragm to pulse cyclically. Since the diaphragm is part of an amplitude modulation circuit, the pulsing causes a concentration related change in its capacitance that is ultimately relayed to a recorder and/or controller as an electrical signal. Cost of an NDIR analyzer is in the vicinity of $3500 with the cost dependent on the user's choice of concentration level, dynamic range, and packaging arrangement.

Infrared analyzers suffer from two significant deficiencies. interference from other molecular species, and lack of sensitivity, stability, and specificity at low concentration levels. For CO measurement, the first of these deficiencies is primarily caused by the presence of CO_2 and H_2O in the sample stream. This interference can, fortunately, be largely eliminated by desiccants, absorbers, optical filters, and filter cells. However, until recently, the second deficiency could only be circumvented by the use of alternative instrumentation (e.g., a gas chromatograph) for engines operating at high power levels (low CO emission rates).

A state-of-the-art advancement in NDIR instrumentation has come about with the development of a fluorescent source carbon monoxide NDIR analyzer (Refs 62 and 63). This analyzer eliminates all unwanted infrared radiation from the sample source and thus from the analysis procedure (i.e., there is no interference from other constituents of the sample stream). The detector is typically solid state or pyroelectric and hence, free from the stability problems associated with the typical gas-filled detector (Ref 62). The instrument uses two isotopes of CO as sources of fluorescent radiation and operates on a single optical path thus eliminating the requirement for a separate standard cell. Although still in the prototype stage, the instrument has been accepted by NASA for use on board the first orbiting skylab (Ref 64). Prototype costs are estimated at $10,000-$15,000. After commercialization, the instrument is expected to reach a competitive cost position with existing NDIR instruments.

Electrochemical

Electrochemical analyzers operate through a wet chemical process where the transducer converts specie concentration to a current signal by an electroxidation or electroreduction reaction. For carbon monoxide determination this reaction is $5CO + I_2O_5 \xrightarrow{\text{120-150 deg C}} 5CO_2 + I_2$ (Ref 65). The instrument is accurate at low concentrations provided the sample stream is properly dried to eliminate possible interference from water. The units cost approximately $2000 to $2500 and are thought to require operation by skilled personnel (Ref 59).

Mercury Vapor Detectors

The basis of operation of these detectors is the reaction between carbon monoxide and mercuric oxide: $CO + HgO \xrightarrow{210\text{ deg C}} CO_2 + Hg$. The elemental mercury liberated in this reaction is measured and related to the carbon monoxide content of the sample stream. Since the analysis can be affected by hydrocarbon interference, sample lines must be cooled to condense out these unwanted species. The primary advantage of mercury vapor detectors is their reputed accuracy at low concentration levels (Ref 59).

Gas Chromatographs

All gas chromatograph instruments are comprised of six basic elements: a carrier gas supply system, a sample injection system, a separation column, a column oven, a detector, and a signal output system. The heart of the system is the separation column which can be either a flame ionization detector, a thermal conductivity detector, or an electron capture detector.

In a flame ionization detector, the change in ion concentration during combustion of organic compounds relates to the carbon content of the sample stream. In a thermal conductivity detector, the difference in the thermal conductivity of the species in the sample stream is responsible for a different ability of each component to conduct heat away from a set of filaments, causing a change in filament temperature. The degree of this change is recorded by the signal detection system and is proportional to each species concentration. The basis for operation of an electron capture detector is the difference in the ability of different compounds to capture "free" electrons. Using nitrogen as a carrier gas, the detector ionizes the nitrogen molecules to liberate free electrons. The change in the electron concentration, recorded as a change in current output, is a measure of the amount and electron affinity of the specie(s) present.

Gas chromatographs are primarily thought of as laboratory tools for use with grab samples from aircraft engine exhausts. However, by installation of an automatic sampling valve, a chromatograph can be easily adapted for continuous monitoring in an emissions measurement program. Contrary to popular belief, chromatographs are easy to operate; it is the interpretation of their data that presents a source of difficulty to the unskilled operator.

Gas chromatographs offer the advantages of wide dynamic range (0.1 - 1000 ppm) and high measurement accuracy. Although the basic laboratory units are expensive (approximately $7000 including recorder), the units can monitor several molecular species concurrently. Further, one particular gas chromatograph, a small (occupies less than 1 ft^2 of bench space), light (35 lb), portable unit, has now been developed to sell at $1250 plus $1000 for the recorder system. Such a unit would be an excellent supplementary tool to an NDIR unit for low level emissions monitoring.

Supplemental

A wet chemical technique also exists for the determination of CO (Ref 65). In this technique, the sample gas is first cooled and passed through an absorption train to remove unburned hydrocarbons, CO_2, and other interfering species. The stream is then heated electrically,converting the CO to CO_2. The CO_2 is then absorbed in a standard barium hydroxide solution and the excess barium hydroxide titrated with hydrochloric acid. The technique is accurate to a lower limit of about 1 ppm. There is no known carbon monoxide monitor which operates on this principle.

A second wet chemical technique for quantitative analysis of carbon monoxide content in a gas stream involves the use of the carbon monoxide indicator tube. When highly purified silica gel, impregnated with ammonium molybdate and a solution of palladium or palladium oxide, is digested in sulfuric acid it forms a silicomolybdate which on exposure to CO forms molybdenum blue. The depth of color in the detector tube varies from faint green to deep blue in proportion to the amount of CO present in the gas sample. This method can be on a continuous basis for sampling CO by aspirating a metered flow of air through the tube at a constant rate and observing the color change with respect to time. The procedure is not now known to be in use in monitoring aircraft exhaust gases; it has, however, been used for sampling aircraft turbine exhausts with some degree of success in the past (Ref 66).

Carbon Dioxide

Carbon dioxide is a major constituent of aircraft engine exhausts. Present in percentage level quantities in both turbine and piston engine exhausts, it is most frequently measured by NDIR analysis equipment. Gas chromatographic techniques are also employed but generally only for laboratory analyses of engine grab samples. Batch Orsat type analyses have been employed in the past (Ref 50), but are no longer in use.

The SAE E-31 Committee recommends NDIR instruments as the standard device for determination of CO_2 in turbine engine exhausts (Ref 36). A description of the principle of operation of NDIR analyzers and gas chromatographs is presented in the discussion of carbon monoxide monitoring equipment.

Total Hydrocarbons

The concentration of total hydrocarbons in aircraft engine exhausts is most frequently measured with a flame ionization detector. Optical spectrophotometers are also used (Ref 66); gas chromatographs and mass spectrometers are used if determination of specific constituent concentrations is required. In all cases, it is imperative that the sample line to the instrument be maintained at 300 to 350 deg F to avoid condensation of the less volatile hydrocarbon constituents in the sample stream.

FID

The principle of operation of flame ionization detector has been previously discussed in the section dealing with carbon monoxide: gas chromatographs. To reiterate, the flame formed by combustion of pure hydrogen with air produces a negligible source of ions. If a sample gas containing hydrocarbons is introduced into the flame, a complex ionization process occurs liberating a large number of ions. By applying a voltage across the flame, a small ionization current is established in the detector system. This current is then directly proportional to the carbon atom concentration of the flame.

FIDs have been shown to have poor measurement characteristics below about 10 ppm in turbine exhausts (Ref 41), although they are reputedly able to make measurements of hydrocarbon concentrations down to 1 ppm. On the more positive side, FIDs can be used for on-line analysis of emissions, have been successfully employed in the field as portable units (Ref 3), can be easily operated by unskilled personnel, and carry the recommendation of the SAE E-31 Committee as an industry standard (Ref 36). Their cost is approximately $5500.

Optical Spectrophotometers

NDIR spectrometers similar to those used for CO and CO_2 can also be used for determination of total hydrocarbons in exhaust emissions. George and Burlin (Ref 66), for example, report collection of grab samples from aircraft exhausts and their analyses with an IR spectrophotometer set at the 3450[illegible]. This technique clearly requires elaborate calibration procedures and has therefore not seen wide application in aircraft emissions measurement programs.

Gas Chromatography

The instrument best suited for the constituent analysis of the total hydrocarbon measurement is the gas chromatograph. Linear temperature programming is generally employed to elute all individual organics with a sensitivity less than 1 ppb (Ref 67). The technique is most frequently applied to grab samples of the exhaust stream. FID units are not suitable for this type of measurement as they are not sensitized for a particular compound but, instead, detect all classes of unburned hydrocarbons (Ref 68).

Mass Spectrometers

Time of flight mass spectrometers operate on a principle of separation of species according to their mass number. The separation is accomplished by ionizing the sample, accelerating the ionic species via a grid system, and allowing the ions to drift through a region at the nominal ion energy. Since heavier ions travel slower than those of lighter mass, a separation of the different molecular constituents is achieved.

Mass spectrometers are expensive units (about $15,000), require the use of highly skilled operators, and are not suited for field use. Their use in aircraft emissions analysis programs has been all but nonexistent.

Nitric Oxide and Total Oxides of Nitrogen

Nitric oxide and total oxides of nitrogen are measured by a variety of overlapping techniques. These methods include classical batch wet chemical colorometric procedures, electrochemical analyzers similar to those used for measurement of carbon monoxide, nondispersive infrared spectrometers for measurement of NO, nondispersive ultraviolet spectrometers for measurement of NO_2, gas chromatographs, faristors, and chemiluminescence monitors. The SAE E-31 Committee presently recommends the use of NDIR units for measurement of NO, NDUV units for measurement of NO_2, and makes no recommendation for total NOx monitoring equipment (Ref 36). However, at this writing, chemiluminescence monitors are undergoing extensive field testing by the EPA and may become the industry standard for continuous measurement of NO and NOx.

Sampling problems associated with measurement of emissions are discussed earlier in this report. However, it is imperative to keep in mind that: (1) NOx can be reduced by CO if catalyzed at elevated temperatures by any of a variety of the metallic surfaces that are frequently employed in sampling lines; (2) NO can be similarly catalyzed to NO_2; and (3) NO_2 can be easily lost in the drying of the exhaust sample prior to analysis (Ref 42).

Wet Chemical Procedures

Many wet chemical procedures for the determination of nitric oxide depend on the oxidation of the oxide to nitrogen dioxide. The sample is bubbled through an acid potassium permanganate solution where all of the nitric oxide present is converted to an equivalent amount of NO_2 (Ref 69). The NO concentration is then determined by an optical measurement of the color intensity produced by the reaction of the NO_2 with appropriate reagents. Since NO and NO_2 are the primary nitrogen oxide constituents of aircraft engine exhausts, it is appropriate to test a given sample twice (or split the sample stream for individual analyses)-- once for determination of the NO_2 content of the NOx and once for determination of the total NO and NO_2 in the sample. The NO concentration is determined by difference.

The Jacobs and Hochheiser technique for determination of NO_2 (Ref 70) is frequently employed in the presence of high concentrations of sulfur dioxide. Air is aspirated through a fritted bubbler in a sampling train containing a nitrogen dioxide absorbing solution. The absorbed nitrogen dioxide is determined colorimetrically as the azo dye. Nitrogen dioxide concentration of the order of parts per hundred million can be determined by this technique. Another method used for NO_2 determination is based on the absorption of nitrogen oxides by a solution of mixed reagent consisting of sulfanilic acid, α-naphthylamine, and acetic acid in a glass bubbler (Ref 71). The color produced is compared to standards or observed spectrophotometrically at a wavelength of 550 nanometers (nm). ASTM designation E1607, issued in 1958, is a modification of the above principle, the major changes being the substitution of N-(1, naphthyl)-ethylene diamine dihydrochloride for α-naphthylene as the coupling agent and the use of a fritted bubbler instead of an ordinary glass bubbler. Again the resultant color can be read with a spectrophotometer set at 550 nm.

In the phenol disulphonic (PDS) acid procedure, the gas sample is fed into an absorbent solution of hydrogen peroxide in dilute sulfuric acid. The oxides of nitrogen (NO and NO_2) are converted to nitric acid by the absorbent and the resulting nitrate ion reacted with PDS to produce a complex whose yellow color is read colorimetrically (Refs 72 and 73). The PDS procedure is recommended for gaseous mixtures containing NOx from 5 to several thousand ppm. It is specific only for the total NOx in the exhaust stream. No definite trend attributable to contaminants in the exhaust stream has been noted for the PDS procedure (Ref 74).

The most commonly used wet chemical analysis method for nitrogen dioxide and nitric oxide is the Saltzman method (Refs 69 and 75). This method is intended for manual determination of nitrogen dioxide in the atmosphere in the range of a few parts per billion to about five parts per million. The sample is obtained by drawing air through fritted bubblers and nitrogen dioxide is absorbed in Griess-Saltzman reagent (Ref 65). A stable pink color is produced and may be read visually or spectrophotometrically at 550 nm. This method is also applicable to the determination of nitric oxide after it is converted to an equivalent amount of nitrogen dioxide by passage through a potassium permanganate bubbler. Ozone and sulfur dioxide are known to interfere with Saltzman measurements (Refs 69 and 74); however, their concentrations in aircraft exhausts are usually not high enough to cause significant difficulty with the technique.

Another technique that has not seen much application to aircraft engine exhaust analysis is the Griess-Ilosvay (GI) colormetric method (Ref 65). A high-pressure mercury vapor lamp is used in the presence of a butadiene solution to oxidize NO photochemically to NO_2. The NO_2 is absorbed in the GI reagent and the intensity of color measured. For simultaneous determination of NO and NO_2, the sample stream is divided into two portions with the NO in one converted to NO_2 by passage through an acidified solution of potassium permanganate. Both streams are then analyzed for NO_2 content by the previously discussed procedure that employs an absorbing solution of sulfanilic acid, N-(1-naphthyl)-ethylenediamine dihydrochloride and acetic acid.

All of these methods are batch type analyses which are slow, require skilled personnel for performance, and do not yield continuous data. Some investigations have incorporated these techniques into continuous analyzers by using a spectrophotometer and appropriate valving. For example, Ganz and Kuznetsuo (Ref 76) have developed an automatic recording gas analyzer based on the measurement of the variation of the pH of a solution with the concentration of the oxides of nitrogen in the gas stream passing through it. Its operating principle is that the interaction of nitrous gases with the absorbent (5 per cent hydrogen peroxide) yields a weak nitric acid solution and the change in concentration of the acid is dependent on the specific gravity and concentration of the gas passing through the solution.

Electro-Chemical Analyzers

Electro-chemical analyzers similar to those used for carbon monoxide can also be used for determination of NO_2 and NOx concentration in exhaust emissions. The units range in cost from approximately $2000 to $3000 with cost dependent on range and the SO_2 concentration in the stream. The principle of operation and the relative advantages and disadvantages of this instrument are discussed in the section on carbon monoxide measurement.

NDIR

NDIR spectrometers similar to those used for CO and CO_2 can also be used for determination of nitric oxide in exhaust emissions. This technique is, in fact, the procedure recommended by the SAE E-31 Committee for NO determination (Ref 36). The procedure is accurate and reliable if care is taken to eliminate interference from other species present in the exhaust, especially water vapor. A combination of optical filters and drying agents are the most widely used methods of discrimination. This interference problem is most acute at low concentrations of nitric oxide.

NDUV

NDUV units have been recommended by the SAE E-31 Committee for NO_2 determination in turbine engine exhausts since it is now accepted that NO and NO_2 are the prime nitrogen oxide constituents in aircraft exhausts. The principle of operation of NDUV units is as NDIR units; only a different portion of the spectrum and a different optical cell path length are employed.

Gas Chromatographs

Gas chromatographs are well suited for the analysis of the oxides of nitrogen especially at low concentration levels where they would make excellent supplemental tools for NDIR and NDUV units. Their relative advantages and disadvantages are discussed in the section on carbon monoxide measurement.

Faristors

Faristor is the trade name of a "plug-in sensor" marked by Environmetrics Inc. These units are low cost ($1750 to $2300) electronic multigas analyzers that are "liquid-state nonohmic variable resistors in which a pollutant-selective activating surface ruptures the gas molecular bonds, releasing energy as a voltage signal proportional to the pollutant concentration" (Ref 77). Faristors are sensitive to NO, NO_2, NOx, and SO_2 with various modular units available for different ranges of each of the species of interest. Avco Lycoming (Ref 39) is evaluating the applicability of these instruments for aircraft exhaust measurements. Their sensitivity in this application is as yet unknown.

Chemiluminescence Monitors

As evidenced above, most of the instruments and procedures for determing oxides of nitrogen depend on coulometric or colorimetric techniques. The chemiluminescent procedure depends instead, upon the formation of electronically excited nitrogen dioxide by the rapid reaction of nitric oxide with ozone and the subsequent emission of optically detectable light (Refs 78, 79, and 80). Total oxides of nitrogen are determined by thermal conversion of the nitrogen dioxide in the sample to nitric oxide and remeasurement of the total NO.

This procedure has a reported sensitivity from 1 ppb to 1000 ppm and offers the added advantages of continuous monitoring without interference from other (pollutant) species typically present in aircraft exhausts. Chemiluminescent units are now available in both modular and self-contained configurations and require only a small vacuum pump as auxiliary equipment. Instrument operation is possible by unskilled personnel; cost per unit is between $5475 and $10,800, depending on the range and configuration requirements and on whether the unit is required to measure NO or NO and NOx.

Application of this instrument to engine exhaust measurement has shown it highly satisfactory for measurement of nitric oxide (Refs 81 and 82). Measurement difficulties have, however, been encountered for measurement of NOx (Ref 40) particularly in turbine exhausts where NOx $\neq$ NO. Chemiluminescence units are now undergoing extensive testing in the EPA's aircraft emissions baseline data collection program; the results of this program should determine its suitability as a standard for NO and NOx emissions quantification.

Sulfur Dioxide

Sulfur oxides in aircraft engine exhaust is produced by the combustion of sulfur impurities in the source fuel. It is generally accepted that all of the sulfur present in the fuel is converted to sulfur dioxide during engine operation; hence, it is standard procedure to calculate, rather than measure, the SO_2 content of the exhaust stream. This can be done from a knowledge of the fuel's sulfur content, and of the fuel-to-air ratio and fuel flow rate for the prescribed engine operating conditions.

Measurement of SO_2 in engine exhaust is most frequently accomplished by batch wet chemical analysis procedures although some of these techniques have been adapted for use in continuous monitoring equipment. The SO_2 content of aircraft exhausts can also be monitored by Faristors, by electrochemical and conductivity analyzers, and by remote spectrometers. These techniques are, at most, infrequently employed and are only mentioned here for completeness.

Wet Chemistry

Katz (Ref 65) reports a large number of wet chemical procedures for determination of SO_2; however only the West-Gaeke (Ref 83) and hydrogen peroxide methods (Ref 69) are widely used.

In the West-Gaeke procedure, the sulfur dioxide is reacted with sodium tetrachlormercurate to form an intermediate dichlorosulfitomercurate ion. This ion is reacted with acid-bleached p-rosaniline and formaldehyde to produce a red-purple color that may be read visually or spectrophotometrically. Nitrogen dioxide is known to interfere with this determination if the NO_2 is present at concentrations greater than that of the sulfur dioxide. Fortunately, the NO_2 can be eliminated as an obscurant by addition of sulfamic acid to the absorbent. The technique is applicable for determination of SO_2 in the range 0.005 to 5 ppm and is more sensitive than the hydrogen peroxide technique discussed below.

In the hydrogen peroxide technique, sulfur dioxide is absorbed in a solution of hydrogen peroxide which oxidizes it to sulfuric acid. The solution acidity is then determined by titration with a standard alkali solution. This method is the preferred procedure if SO_2 is the principle acid or basic atmospheric pollutant present in the exhaust gas stream; it is simpler to conduct than the West-Gaeke procedure and applicable in a concentration range of about 0.01 to 10 ppm.

Faristors

The discussion of Faristor operating principles in the section on NO/NOx measurement is applicable here. The Avco effort (Ref 39) will be the first known application of these sensors to aircraft exhaust emissions. Lockheed-California also has Faristors, but their use has not as yet been reported.

Electrochemical Analyzers

The discussion of electrochemical operating principles in the section on CO measurement is applicable here. There has been no known attempt to measure the SO_2 content of aircraft exhausts with such analyzers.

Conductivity

The instruments developed for SO_2 measurement via conductivity techniques depend upon the H_2O_2 wet chemical technique. These instruments have been specifically tailored for ambient, rather than source, emissions monitoring programs. They can, of course, be used in a source measurement program if the source stream is diluted to reduce the SO_2 concentration to detectable limits.

Spectrometry

As discussed by Broderick (Ref 59) remote monitoring of SO_2 by correlation spectrometry is technically possible but economically infeasible. Further development of the technique will be necessary before it can be employed in a source emissions analysis program.

Aldehydes

Wilson's paper (Ref 84) and Stahl's survey (Ref 85) contain thorough reviews of the procedures for the determination of aldehydes in air. All methods for aldehyde determination-- either for total aldehydes or for individual species (e.g., formaldehyde, acrolein)-- depend upon wet chemical analysis. The only procedure for continuous aldehyde analysis is the Technicon Air Monitor IV-- at a price of $6400. This monitor makes use of the 3-MBTH wet chemical procedure (Ref 86) for total aliphatic aldehydes measured in equivalent formaldehyde units. (A modified Schiff procedure using rosaniline and dichlorosulfulomercurate is also available.)

Total Aldehydes

A summary of the available methods for total aldehyde measurement is also given in NREC Report No. 1134 (Ref 1) and is not repeated here. The most extensively used method for determination of total water-soluble aliphatic aldehydes (measured as formaldehyde) are the 3-Methyl-2-benzothiazolone Hydrozone Hydrochloride (MBTH) method. This procedure was developed by Sawicki (Ref 86) and subsequently refined by Hauser and Cummins (Ref 69). In this procedure, 3-MBTH is reacted with the sample in the presence of ferric chloride in a sulfamic acid solution to form a blue cation dye that is measured spectrophotometrically at 628 mμ. The procedure is specific for aldehyde concentrations as low as 2 ppb. Aromatic amines, heterocyclic imino compounds, and carbozoles cause interference with the analysis; however, since most of these compounds are neither gaseous nor water soluble, they do not generally interfere in atmospheric or exhaust gas analysis.

The disadvantage of the MBTH procedure is that the reaction is more sensitive to formaldehyde than other aliphatic aldehydes or branched-chained and unsaturated aldehydes (Ref 85). This causes an unequal response to each aldehyde which has been reported (Ref 51) to be responsible for inaccurate (low) measurement of total aldehydes in aircraft turbine exhausts. Further, high ratios of the concentration of SO_2 or olefins to total aldehyde concentration at low (1 ppm) aldehyde levels may cause errors in the measured results (Ref 87).

Two other techniques for carbonyl measurement are given in Reference 87. Their suitability for turbine exhaust measurements are also discussed.

Formaldehyde and Acrolein

There are a variety of procedures for measurement of individual aldehyde concentrations; for example, the 4-hexylresorcinol procedure exists for acrolein (Ref 69) and the chromotropic acid method is used for formaldehyde (Ref 69). These procedures are applied because it is frequently necessary to distinguish between total aldehydes and the two major aldehyde constituents of aircraft exhaust-- formaldehyde and acrolein. This is done in efforts to find correlations between the odor and irritant properties of engine exhaust gases (Ref 88).

In the chromotropic acid method, formaldehyde reacts with the acid to produce a purple-violet monocationic chromogen whose color intensity (read spectrophotometrically at 580 mμ) is proportional to the formaldehyde concentration. Fromic acid, dextrose, methanol, phenols, olefins, and aromatic hydrocarbons and similar compounds that decompose under the test procedure are also detected; their presence in the exhaust stream will cause somewhat low measurements. The technique has a sensitivity range of 0.01 to 200 ppm.

Acrolein is also detected by a spectrophotometric procedure. As discussed by Katz (Ref 65), acrolein reacts with 4-hexylresorcinol in the presence of mercuric chloride and trichloroacetic acid to produce a blue-purple color whose intensity can be read by a spectrophotometer or colorimeter at 605 mμ. The procedure is quite sensitive and specific; most organic constituents of the exhaust stream will not interfere with the determinations. The technique has a reported sensitivity range from 20 ppb to 10 ppm.

Particulates

The major problem ascribed to measurement of particulate emissions from aircraft is one of definition. All particulates, large or small, liquid or solid, emanating from an emissions source are included in the Los Angeles County Air Pollution District (Ref 89) definition of particulate matter. Specifically, they describe particulate matter as any substance, liquid or solid, except unbound water, that exists in a finely divided form at ambient conditions. Clearly, this definition means that vapors of low volatility, for example, hydrocarbons, are counted in two categories-- as both hydrocarbons and particulates. As a result, most aircraft emissions measurement programs are concerned with particulate matter on a dry basis; that is, with the liquid droplets removed from the sample stream or with the sampling and collecting system maintained at a sufficiently elevated temperature to avoid vapor condensation.

A good example of the discrepancy in the measured results according to these two definitions is provided in Bristol's paper (Ref 52) on aircraft gas turbine engine emissions. Here it is shown that particulates in the same exhaust stream are as much as 2 to 3 orders of magnitude higher in concentration if measured by the Los Angeles "wet" procedure than they are if measured on a dry basis.

Both solid and liquid particulate emissions are of concern to air pollution control agencies. However, in the opinion of the NREC staff, no particulate measurement device has been developed which realistically simulates the condensation of vapors as it occurs in an aircraft engine exhaust plume. Therefore, the only particulate measurements which have any quantitative significance are those which indicate concentrations of solid or "dry" particulates.

NREC Report No. 1134 (Ref 1), the study by Broderick (Ref 59), and the Los Angeles Source Testing Manual (Ref 89) provide thorough summaries of the instruments and procedures available for particulate mass, size, and size distribution measurement. As a result, only a summary of the more common types of particle detectors now available is presented here.

Collection devices that are most commonly used in monitoring aircraft particulate emissions are based on filtration and impingement (wet or dry) techniques.

Filters remove particles from a gas stream by direct interception, by inertial collection, by diffusional deposition, by electrical attraction, and by gravitational attraction. In a given instrument one or more of these mechanisms may be employed; details of these principles are given in Ref 90. Filtration schemes are generally applicable for particles in the 0.1 to 10 micron (diameter) range; in most cases, the analysis is completed by direct weighing of the filtrate and filter medium. Types of filters and filter holders are discussed in Reference 90; typical cost of the widely used "Hi-Vol" sampler which is based on the direct filtration principle is about $200 to $300.

Impactors or impingers are generally built as cascades to simultaneously collect and classify particles by both mass and size. Impactors are less frequently used in aircraft particulate emissions measurement programs than direct filtration devices; their predominant application has been with aerosols and dust laden process streams. Impactors cost from $750 to $2000 with cost dependent upon the stage requirements and upon the necessity (or lack of necessity) for maintaining the sample stream at an elevated temperature.

Mass monitors are devices that allow real-time measurements of particulate concentration over a size range from 0.01 to 15 microns and at concentrations up to 100,000 μgms/m^3. These instruments operate by drawing the sample gas through a chamber where the particles take on an electrostatic charge. The stream then passes over a vibrating piezoelectric sensor where an electric field forces the particles into contact with the sensor. The resonant frequency of the sensor is thus reduced in direct proportion to the mass of the adhering particles; this output signal can be monitored with standard digital counting equipment (Refs 91 and 92). Cost of a mass monitor is $1800 to $2000, a complete system including a monitor, indicator/printer, auxiliary vacuum pump, and cabinet, costs $4000. One report of the use of particle mass monitors in an automotive emissions program showed a deviation of ±30 per cent from deposits collected via filtration equipment; this may be due to the presence of organic particles with the lead particles or to temperature and humidity fluctuations in the diluted exhaust streams (Ref 93). Clearly, further development work is still necessary on this type instrument.

Other existing detection devices for particulate monitoring that do not depend upon optical scattering techniques include electrical mobility analyzers and beta gauge systems. Electrical mobility analyzers are used with particles 0.005 to 1.0 microns in diameter and are based on the attraction of charged particles to a metal surface of opposing charge (Ref 59). Beta gauge systems use a paper tape sampler to collect particulate matter on a filter; the tape is then placed between a beta source and a radiation detector. The attenuation of the source energy is proportional to the particle concentration (Ref 93). Both of these instruments are in the prototype stage; the beta guage system has been successfully employed in an automotive emissions program (Ref 93).

Microwave laser radar and microwave spectrometers are both available for measurement of particle size and density in exhaust streams (Ref 94). Units based on electrostatic precipitation are also available (Ref 94).

An interesting optical device for particle monitoring is the 0.1 to 10 micron (diameter) range is the integrating "nephelometer" described by Charlson (Ref 95). This device measures the scattering coefficient of light caused by particulate matter in the sample stream and automatically relates the measurement to particle concentration and to visibility. The instrument is so designed that nearly the total solid angle from full forward to direct back-scattering is observed. A serious deficiency in the instrument is the needed assumption of a constant particle size distribution and composition in its calibration (Ref 96). The instrument and sampling line can be maintained at a sufficiently elevated temperature to avoid condensation of the less volatile matter in the sample stream. A nephelometer has recently been tested with aircraft engines at the Naval Air Propulsion Test Center, but the results of the test are unknown (Ref 97). Unit cost is about $5300.

Most other light scattering or video scan devices have been developed primarily for measurement of the size distribution of a sample, rather than for determination of total particulate concentration. These devices are expensive ($4000 for a sensor to $35,000 for complete systems), have a limited dynamic range (e.g., 30), and have an unsatisfactory lower sensitivity limit of about 0.1 microns.

Condensation nuclei counters are used for determination of the concentration of particulate matter in the 0.001 to 1 micron (diameter) size range. Particles of this size are important from an emissions standpoint since they act as nuclei for the photochemical smog reactions. Further, particulates in this size range are respirable and thus potential health hazards. It appears that the majority of the particulate emissions from aircraft engines fall into this category (Ref 58) and are clearly not measured by convention filtration or impingement techniques. The basis of operation of condensation nuclei counters is the ability of condensation nuclei to act as centers for the condensation of water in a supersaturated environment. Through the condensation of the water on the nuclei, droplets are formed of visible size. Standard optical techniques are then applied for their detection and measurement (Ref 98). Condensation nuclei counters cost in the vicinity of $6500,with compact portable units available at about $4500.

Most currently available condensation nuclei monitors operate in a range from 0.001 to 0.1 microns with a 20 per cent accuracy. The Department of Transportation Systems Research Center in Cambridge, Mass. is therefore developing a portable counter to fulfill the need for an instrument operating in the range from 0.001 to 1 micron (Ref 59). The design goals for this instrument include the ability to accept sample streams with concentrations from 10 to 10^6 particles/cc at input ambient pressures from 0.05 to 1.0 atm with intake temperatures from -60 deg C to 200 deg C and with a measured accuracy of 10 per cent across a spectrum of 10 size ranges. Reference 59 contains further reference details on the need for condensation nuclei monitors for aircraft particulate emissions monitoring.

Smoke

Three general techniques are applicable for smoke measurement. These are:

1. Subjective analysis where visual comparison of plume darkness is made with a graded chart.
2. Light extinction where a light meter measures the attenuation of a light source shone directly through a sample of the exhaust plume.
3. Indirect reflectance where the amount of light reflected by filter paper through which a fixed volume of the sample stream has passed is measured.

In all cases, a smoke number is calculated or assigned which relates the darkness of the plume to the amount of light absorbed and scattered by the smoke. NREC Report No. 1134 (Ref 1) and the reports of Shaffernocker (Ref 99) and Toone (Ref 100) contain detailed discussion of these techniques.

The first priority of the SAE E-31 Committee was to develop a method and device for monitoring smoke emissions from aircraft. The committee agreed that, ". . . a stained filter technique was the most satisfactory even though it missed the desire for a measurement system that was directly convertible into degree of visible obscuration (Ref 101)." This decision led to the SAE ARP-1179 (Ref 55) which specifies test, sampling (e.g., probe orientation), and analysis techniques to be followed to insure conformity of smoke measurement in the aircraft industry. At the present time, the committee is considering modifications to the sampling procedures established in the ARP in light of information made available since its release.

Several instruments have been constructed which conform to the specifications of ARP 1179. One unit has a sale price of $3200 without a sample line or a reflectometer; it is not, however, generally available.

As recognized by the E-31 Committee at its inception, the stained filter technique does not lead directly into a measure of visibility extinction. However, correlations have been developed which relate the smoke meter reading to the mass concentration of dry particulates (Ref 102) and the opacity of the engine exhaust jet (Ref 103).

Odor

NREC's discussion of the origin and measurement of odor in aircraft engine exhausts (Ref 1) is still an adequate and appropriate summary of this emissions problem. The report by Sullivan (Ref 104) the Public Health Service and the papers by Dravnieks (Ref 56) and Fish (Ref 105) are more recent surveys of the general topic of odorous emissions; Sullivan's study does contain a brief section devoted to aircraft odors.

Perhaps the most relevant statement about odor is made by Fish (Ref 105) when he states ". . . with few exceptions, we do not yet know how to apply meaningful weighting factors to obtain a useful subjective measurement of odor based on qualitative and quantitative measures of gas concentration." Studies by Dravnieks (Ref 106) and Arthur D. Little, Inc. (Ref 107) confirm this contention by identifying the composition of odorous compounds in diesel engine exhaust (by, for example, gas chromato graphic separations) but by failing to develop adequate correlations of these concentrations with a suitable sensory scale. Reference 108 contains a review of federally sponsored research on diesel engine exhaust odors.

Not even this latter type of analysis has been undertaken for gas turbine exhausts. Lozano et al (Ref 50) do, however, report odor dilution thresholds for turbine engines as a function of operating mode (power level) and engine type.

As stated in an earlier section, the SAE E-31 Committee is planning to address itself to this emissions problem in the near future.

Instruments Under Development

The principle of operation of the NO-NOx (and O_3) chemiluminescence monitor involves measurement of the light energy emitted as the specimen of interest is reacted with another gaseous specie. This principle is by no means restricted to the determination of oxides of nitrogen and ozone; systems based on the principle have already been marketed for determination of sulfur dioxide and hydrogen sulfide (Ref 102). EPA is also developing similar methods for measurement of formaldehyde, aromatic hydrocarbons, chlorine, fluorine, hydrogen chloride, and some metals (Ref 109).

A device based on ultraviolet absorption has been designed to monitor unburned hydrocarbons in auto exhaust (Ref 110). In the sample chamber the exhaust gas is exposed to UV radiation. A sensor tuned to a wavelength band between 1850 and 2250 Angstroms then measures the degree of absorption of the radiation by the sample. Since olefins and aromatic hydrocarbons are excellent absorbers in this band (but oxygen, water, and other common gases are not), the instrument is particularly well-suited for determination of reactive hydrocarbons.

A device for separating reactive and unreactive hydrocarbon in engine exhaust has also been developed by Groth and Zaccardi at Pratt & Whitney (Ref 111). This unit is subtractive in nature; that is, chemical absorbents are used in series with a heated FID to remove the reactive hydrocarbons from the sample. In this way, the concentration of the reactive species that participate in the photochemical smog reactions can be determined.

McClatchie (Ref 62) reports that a single path fluorescent NDIR unit similar to that constructed for monitoring CO is under development for NO measurement. The unit promises to have greater sensitivity in the lower concentration ranges than conventional NDIR instruments and will be free of interference from water vapor and other obscurants.

Broderick (Ref 59) discusses the newly-developed technique of applying remote Raman spectroscopy to trace gas analysis. Until development of the laser,the procedure was primarily a laboratory curiosity due to the requirement of lengthy exposure times with high-power mercury arc lamps (Ref. 112). This analysis technique depends on light scattering; light absorbed by a molecule is re-emitted at a shifted frequency. This and the incident frequency relate to specific character-excitation frequencies of the scattering molecule. If the energy of the Raman photons for a particular molecule is known, measurement of the scattering relates to the concentration of that specie in the sample stream. Champagne (Refs 40 and 113) reports a contract between the Aero Propulsion Laboratory and Avco Everett for the development of an engineering prototype of a field unit that could be used at either an aircraft test cell or at a flight line location. The two year program will examine the technological feasibility of monitoring CO, CO_2, NO and NOx, and total organics (C-H stretch band) as they are emitted in aircraft exhausts. The first phase of this program is now underway and will determine the appropriate molecular energy bands and potential obscurations (e.g., CO by CO_2 or CO_2 by CO) at the elevated temperatures (1200 to 1800 deg F) of interest.

Hinkley and Kelley discuss (Ref 114) the development of tunable semi-conductor diode lasers which show promise in the creation of extremely sensitive and accurate NDIR instruments. As discussed by Broderick (Ref 59) such diodes could be "tuned" to specific wavelengths to permit monitoring of such species as the individual components of the total hydrocarbon emission. An instrument specific to NO and which depends on tunable infrared radiation from a Raman spin-flip laser has been reported to detect NO contentrations in air samples at concentrations as low as 0.01 ppm (Ref 115).

LIDAR or Light Detection and Ranging systems have been proposed as atmospheric probes to measure and detect particulate concentrations in the atmosphere. These instruments depend on lasers as power sources and on back scattering measurements to determine particle size distribution and number density. LIDAR is a tool for remote monitoring programs; one drawback to its use is the necessity to make a priori assumptions pertaining to particle size distribution and index of refraction for the purpose of instrument calibration. Reference 116 contains a review of the technique and of its potential application as a pollution monitoring tool.

Dix et al (Ref 117) discuss the use of a mass spectrometer as a probe for studying the chemical kinetics of the formation of oxides of nitrogen in a simulated gas turbine combustor. The probe is suitable for measurement of mole fractions in the 10^{-3} to 10^{-4} range, but requires further engineering development before use as a mobile monitor for engine emissions.